

## IMPROVED TEMPLATES FOR PHOTOMETRIC REDSHIFTS OF SUBMILLIMETER SOURCES

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### ABSTRACT

There is growing evidence that some star-forming galaxies at  $z > 1$  are characterized by high efficiencies and specific star formation rates. In the local universe, these traits are shared by “active” blue compact dwarf galaxies (BCDs) with compact and dense star-forming regions. The spectral energy distributions (SEDs) of these BCDs are dominated by young massive star clusters, embedded in a cocoon of dust. In this Letter, we incorporate these BCD SEDs as templates for two samples of high-redshift galaxy populations selected at submillimeter wavelengths. Because of the severe absorption of the optical light, the featureless mid-infrared spectrum, and the relatively flat radio continuum, the dusty star-cluster SEDs are good approximations to most of the submillimeter sources in our samples. In most cases, the active BCD SEDs fit the observed photometric points better than the “standard” templates, M82 and Arp 220, and predict photometric redshifts significantly closer to the spectroscopic ones. Our results strongly suggest that the embedded dusty star clusters in BCD galaxies are superior to other local templates such as M82 and Arp 220 in fitting distant submillimeter starburst galaxies.

*Subject headings:* galaxies: high-redshift — galaxies: starburst — infrared: galaxies — submillimeter

*Online material:* color figure, machine-readable table

### 1. INTRODUCTION

The extension of the photometric redshift technique to the far-infrared (FIR) and radio spectral ranges has proven to be a useful tool to investigate the population of distant submillimeter sources (Smail et al. 1997; Barger et al. 1998; Hughes et al. 1998) that, because of heavy dust obscuration, may have optical counterparts that are too faint for a spectroscopic identification (e.g., Barger et al. 1999). This technique, first proposed by Carilli & Yun (1999), initially exploited only the radio-to-submillimeter spectral index as a redshift indicator and is still hotly debated because of the degeneracy between increasing redshift and decreasing dust temperature (Blain 1999; Blain et al. 2003; Aretxaga et al. 2005). Nevertheless, it has also recently been extended to other bands (Greve et al. 2004; Eales et al. 2003), including new *Spitzer* data (e.g., Appleton et al. 2004; Frayer et al. 2004). The templates commonly used to fit the FIR-to-radio spectral energy distribution (SED) of high-redshift dusty galaxies are those of well-studied, evolved starburst galaxies in the local universe (typically Arp 220 and M82) or active galactic nuclei (AGNs; e.g., Aretxaga et al. 2003). This approach assumes that dusty starburst galaxies at high redshift are characterized by the same physical properties as local “standard” starburst galaxies.

However, there is growing evidence that some starburst galaxies at  $z > 1$  are characterized by a different regime of star formation. Bauer et al. (2005) have shown that the specific star formation rate (SSFR  $\equiv$  SFR/galaxy mass) at  $z > 1$  is significantly higher than observed in the local universe (see also Feulner et al. 2005 and Greve et al. 2005). New *Spitzer* data reveal that a significant fraction of high-redshift sources are characterized by the absence of polycyclic aromatic hydrocarbon (PAH) features in their mid-IR spectra (Houck et al. 2005). Houck et al. (2005) interpret these observations as a possible indication for AGN-powered galaxies, but a lack of PAH features is also observed in extragalactic, extremely compact star-

forming regions (Thuan et al. 1999; Houck et al. 2004; Galliano et al. 2005). Finally, many high- $z$  submillimeter galaxies show dust obscuration much more extreme than observed in local standard starburst templates (Hammer et al. 2005) and may more closely resemble highly efficient maximum-intensity starbursts (Meurer et al. 1997; Somerville et al. 2001; Greve et al. 2005).

The blue compact dwarf galaxies (BCDs) found in the local universe are certainly less luminous and much less massive than the submillimeter starburst galaxies found at high redshift. They are also more metal-poor, and therefore distinct from the massive “SCUBA galaxies” and Lyman break systems that are already chemically enriched at  $z \lesssim 3$  (Pettini et al. 2001; Tecza et al. 2004; Shapley et al. 2004). However, a subclass of them, “active” BCDs (Hirashita & Hunt 2004), seems to share one characteristic with the high-redshift submillimeter population: extreme star-forming modes. Active BCDs host extremely compact, very young, super star clusters, which are responsible for a very efficient SSFR and which dominate their SEDs (Vanzi & Sauvage 2004; Hunt et al. 2005). The intense SSFR and the compactness of the star-forming regions make the infrared SEDs of active BCDs quite different from “classical” starburst galaxies, often being broader and/or warmer, and featureless (Hunt et al. 2005). The youth of these systems tends to make the radio emission predominantly thermal rather than synchrotron (Klein et al. 1991; Hunt et al. 2005). Super star clusters in BCDs can also be heavily embedded in dust, which makes the stellar and nebular radiation heavily absorbed even in the near-IR (Hunt et al. 2001). These extreme properties of BCDs suggest that they may represent a scaled down version of the extreme starburst galaxies at high redshift. In particular, BCDs could provide better templates for the SEDs of distant starburst galaxies, thus enabling more accurate photometric redshifts.

In this Letter we test this hypothesis by comparing the SEDs of local BCDs (Hunt et al. 2005) with the photometric measurements of high-redshift submillimeter galaxies having secure spectroscopic identifications and redshifts. We show that BCD templates generally provide a better match to the SEDs of submillimeter/SCUBA galaxies and improve significantly the accuracy of photometric redshifts.

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TABLE 1  
PHOTOMETRIC REDSHIFTS  $z_{\text{phot}} - z_{\text{spec}}$  AND RESIDUALS FOR SUBMILLIMETER-SELECTED SCUBA SOURCES WITH VLA AND *SPITZER* DATA

SOURCE	$z_{\text{spec}}^a$	$\langle \text{Res.} \rangle^b$	II Zw 40				NGC 5253 $\alpha = -0.1$ $A_V = 10$ (5)	SBS 0335-052 $\alpha = -0.3$ $A_V = 30$ (6)	M82 (7)	Arp 220 (8)
			$\alpha = -0.5$		$\alpha = -0.1$					
			$A_V = 30$ (1)	$A_V = 20$ (2)	$A_V = 30$ (3)	$A_V = 20$ (4)				
CFRS 14.1157	1.15	0.15 (5)	-0.75	-0.75	-0.65	-0.65	-0.35	0.95	-0.35	-0.95
Frayser 199	1.06	0.32 (8)	-0.46	0.64	-0.36	0.64	1.64	0.34	2.14	1.64
LE 850.1	2.15	0.36 (2)	-0.95	0.45	-0.95	0.45	1.65	0.25	3.85	1.05
LE 850.8	0.85	0.44 (4)	-0.35	0.35	-0.35	0.25	0.85	0.55	2.35	1.85
LE 850.14	2.40	0.23 (4)	-1.40	-0.30	-1.40	-0.30	0.80	-0.40	3.40	0.80
LE 850.18	2.69	0.25 (8)	-1.69	-0.29	-1.69	-0.29	0.81	-0.69	3.31	0.51
$\langle dz \rangle$			-0.93	0.02	-0.90	0.02	0.90	0.17	2.45	0.82
Std. dev.			0.53	0.54	0.55	0.50	0.73	0.61	1.52	1.00

<sup>a</sup>  $z_{\text{spec}}$  from Higdon et al. (2004), Frayer et al. (2004), Chapman et al. (2005), Ivison et al. (2004), Chapman et al. (2005), and Egami et al. (2004).

<sup>b</sup> Lowest residuals for  $z = z_{\text{spec}}$ , obtained with the template in parentheses.

## 2. THE BCD SED TEMPLATES

The SEDs from  $5 \mu\text{m}$  to  $20 \text{ cm}$  of low-metallicity active BCDs are well modeled by dusty massive star clusters (Hunt et al. 2005). We have taken three cases from Hunt et al. (2005): NGC 5253, II Zw 40, and SBS 0335-052, which are characterized by different amounts of dust extinction:  $A_V = 10, 20,$  and  $30 \text{ mag}$ , respectively. Because the SED of SBS 0335-052 is very unusual, peaking at  $\sim 30 \mu\text{m}$ , we have also included another best-fit model for II Zw 40 with  $A_V = 30 \text{ mag}$ . Also for II Zw 40, we adopted two possible values for the radio slope: pure thermal  $\alpha = -0.1$  and supernova-like  $\alpha = -0.5$ , both of which are consistent with the data.

Rather than the entire observed BCD SED, we adopt here only the dusty star-cluster SED, as given by Hunt et al. (2005), which is based on DUSTY (Ivezić & Elitzur 1997) models. Because of the large optical depths, the rest-wavelength optical bands in these SED templates are highly reddened and absorbed. The observed optical SEDs of BCDs are not well modeled by the dusty clusters, because the optical light arises from regions outside of the clusters or at least from regions that are not subject to their high extinction. We do not consider such emission in our SED templates.

The BCDs that we are using as SEDs are generally metal-poor. However, the interstellar medium metallicity determines, at least in part, *only* the dust content (e.g., Edmunds 2001), so that it becomes a scaling factor rather than a shaping factor in the SED. Observationally, these star-cluster SEDs are applicable to a wide range of metal abundances, from highly subsolar (SBS 0335-052,  $\sim 2.5\% Z_\odot$ ) to  $\sim$ solar (He 2-10; Hunt et al.

2005). Hence, the SEDs we are using to model high- $z$  sources are essentially independent of metallicity.

## 3. BCDs VERSUS SUBMILLIMETER GALAXIES WITH *SPITZER* DATA

A few submillimeter sources (e.g., Smail et al. 1997; Barger et al. 1998; Hughes et al. 1998) have recently been observed with *Spitzer* (Egami et al. 2004; Frayer et al. 2004; Ivison et al. 2004; Higdon et al. 2004). Such new data allow a more detailed analysis of the IR-to-radio SED of these distant starburst galaxies than previously possible. Among the submillimeter galaxies observed with *Spitzer*, we have selected those with secure spectroscopic redshifts.<sup>3</sup> These six sources and their basic properties are listed in Table 1. None of them seems to host a powerful AGN, at least according to their optical spectra. Due to the limited space available in this Letter, the photometric points for only three of the six sources are plotted in Figure 1.

We have fit the observed SEDs with the six templates described in § 2. The “fit” is a scaling normalization to minimize residuals and a calculation of the remaining (logarithmic) rms deviations. For comparison with the templates adopted in the past, we also fit the SEDs with the spectrophotometric models of M82 and Arp 220 given by Bressan et al. (2002). In total, we consider eight templates: six variations of BCD star clusters, M82, and Arp 220. In Figure 1 we show examples of the various

<sup>3</sup> A seventh source would also be available, but it is lensed and therefore more complex to interpret.

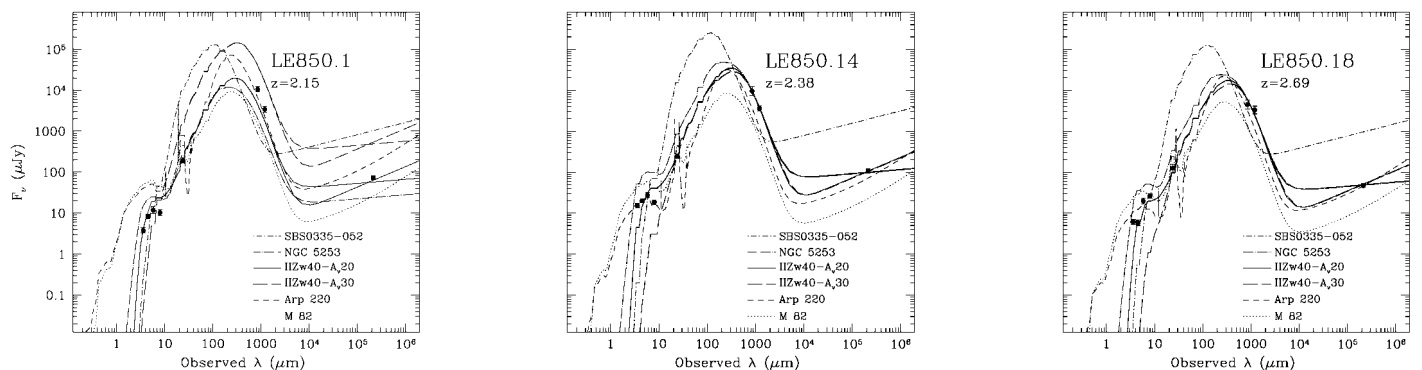


FIG. 1.—SEDs of radio-identified submillimeter sources (Scott et al. 2002; Ivison et al. 2002; Egami et al. 2004; Ivison et al. 2004), with various starburst templates normalized to the data (see text). The best-fit BCD SED templates are II Zw 40 ( $A_V = 20 \text{ mag}$ ,  $\alpha = -0.5$ ) for LE 850.1 and II Zw 40 ( $A_V = 20 \text{ mag}$ ,  $\alpha = -0.1$ ) for LE 850.8 and LE 850.14. [See the electronic edition of the Journal for a color version of this figure.]

TABLE 2  
PHOTOMETRIC REDSHIFTS  $z_{\text{phot}} - z_{\text{spec}}$  AND RESIDUALS FOR SUBMILLIMETER-SELECTED SCUBA SOURCES WITH VLA DATA ONLY

SOURCE <sup>a</sup>	$z_{\text{spec}}$ <sup>a</sup>	$\langle \text{Res.} \rangle^b$	II Zw 40				NGC 5253 $\alpha = -0.1$ $A_V = 10$ (5)	SBS 0335-052 $\alpha = -0.3$ $A_V = 30$ (6)	M82 (7)	Arp 220 (8)
			$\alpha = -0.5$		$\alpha = -0.1$					
			$A_V = 30$ (1)	$A_V = 20$ (2)	$A_V = 30$ (3)	$A_V = 20$ (4)				
FN 1-40 .....	0.45	3	0.35	0.45	0.25	0.35	0.35	4.45	0.65	1.05
FN 1-64 .....	0.91	1	-0.01	0.09	-0.11	-0.01	0.09	4.39	0.29	0.59
030231.81+001031.3 .....	1.32	3	1.28	1.38	1.18	1.28	1.18	5.68	1.58	1.88
030236.15+000817.1 .....	2.44	7	-0.23	-0.14	-0.34	-0.23	-0.34	4.57	0.07	0.47
030244.82+000632.3 .....	0.18	3	1.22	1.32	1.02	1.12	1.02	6.82	1.42	1.82
105151.69+572636.0 .....	1.15	3	0.65	0.75	0.55	0.55	0.55	5.85	0.95	1.35
$\langle dz \rangle$ .....			0.25	0.26	0.14	0.19	0.10	4.89	0.47	0.79
Std. dev. ....			1.13	1.05	1.20	1.18	1.12	0.83	1.05	1.02

NOTE.—Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

<sup>a</sup> Sources and  $z_{\text{spec}}$  from Chapman et al. (2002, 2005).

<sup>b</sup> Lowest residuals for  $z = z_{\text{spec}}$  obtained with this template.

templates redshifted to the spectroscopic redshift and scaled to best fit the photometric measurements. In Table 1 we give the rms residuals for the best-fit template evaluated at the spectroscopic redshift. In four of the six cases, the BCD templates fit significantly better the observed photometric points than either the M82 or Arp 220 templates.

We have also tested the capability of each template to reproduce the spectroscopic redshift through the photometric redshift technique. First, the SEDs were convolved with the *Spitzer*

filters. Then, by finding the minimum of  $\chi^2$  residuals as a function of redshift for the various templates, we derived the photometric redshift for each source. Table 1 reports the photometric redshifts obtained for each template. It is impressive that the BCD templates *always* provide a photometric redshift closer to the actual spectroscopic redshift than obtained with the M82 or Arp 220 templates.

The smallest average  $z_{\text{phot}} - z_{\text{spec}}$  and standard deviation are obtained with the II Zw 40 model having  $A_V = 20$  mag and a thermal radio spectrum. If we were to calculate photometric redshifts of the objects in this sample using this SED, we would obtain a mean and standard deviation of  $\langle z_{\text{phot}} - z_{\text{spec}} \rangle = 0.02 \pm 0.50$ . If we use SBS 0335-052 ( $A_V = 30$  mag,  $\alpha = -0.3$ ), we would obtain a mean and standard deviation of  $\langle z_{\text{phot}} - z_{\text{spec}} \rangle = 0.17 \pm 0.61$ . Were we to use Arp 220 (M82), we would obtain results inferior to both of these with large means and significantly larger scatters:  $\langle z_{\text{phot}} - z_{\text{spec}} \rangle = 0.8(2.5) \pm 1.0(1.5)$ .

The reason that BCD SEDs better match the observed SEDs in these high- $z$  submillimeter galaxies with *Spitzer* IRAC+MIPS data is a combination of some or all of the following effects: (1) the  $\lesssim 5 \mu\text{m}$  region (stellar light) is much more absorbed in some BCDs than in the M82 and Arp 220 templates; (2) all (active; see Hunt et al. 2005) BCDs are featureless in the mid-IR; (3) the infrared bump is broader in some BCD SEDs; and (4) the flatter thermal radio continuum of some BCDs better matches the radio observations in some sources.

#### 4. BCDs VERSUS SUBMILLIMETER GALAXIES WITH ONLY RADIO DATA

Thanks to the recent spectroscopic surveys of submillimeter sources with radio counterparts, large samples of submillimeter sources with secure spectroscopic redshifts are now available (e.g., Chapman et al. 2005). For most of these sources *Spitzer* data are not yet published, making unfeasible a detailed analysis such as the one performed in the previous section. However, we can test the photometric redshift technique by exploiting the  $850 \mu\text{m}$  and radio data, as was done for most submillimeter sources in the past.

We have compiled a list of all SCUBA sources with spectroscopic redshifts (Chapman et al. 2002, 2005), discarding those lensed and with multiple counterparts to avoid complications that may arise in the interpretation of the SED in these cases. We have also discarded sources whose spectra show clear signatures of an AGN, since in this Letter we focus on the

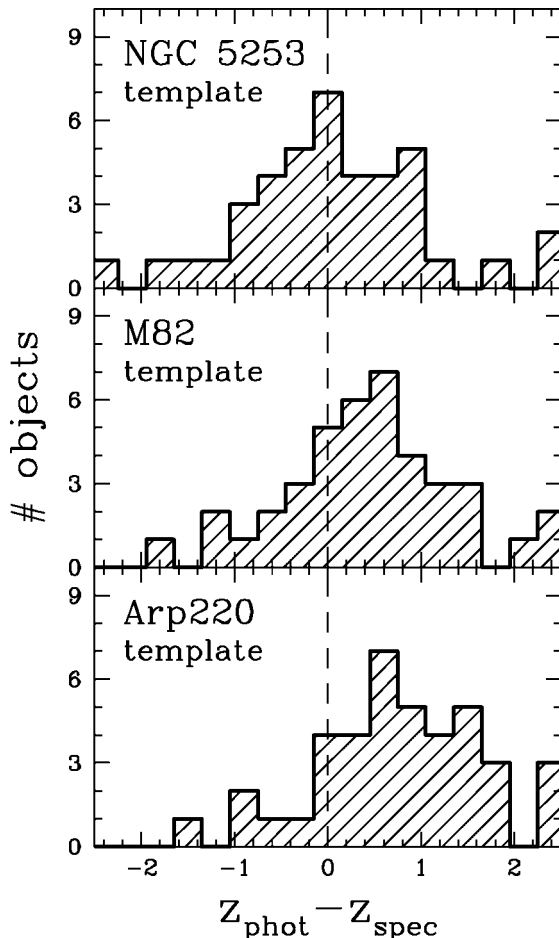


FIG. 2.—Histograms of the  $z_{\text{phot}} - z_{\text{spec}}$  best-fit BCD template, NGC 5253, and the two standard templates, M82 and Arp 220. The spread is similar for all three templates, but the zero mean of NGC 5253 is evident.

interpretation of the SEDs due to star formation alone. These selection criteria resulted in a sample of 40 sources, which are listed in Table 2.

For each source we estimated the submillimeter-to-radio photometric redshift by using both the BCD templates and the classical templates M82 and Arp 220, as discussed in the previous section. We found that in 63% (25/40) of the cases, BCD templates provide a photometric redshift that is closer to the spectroscopic one than the M82 or Arp 220 templates. Moreover, the mean difference  $\langle z_{\text{phot}} - z_{\text{spec}} \rangle$  averaged over the sample is significantly reduced for the BCD templates ( $\sim 0.1$  for NGC 5253), relative to M82 ( $\sim 0.5$ ) or Arp 220 ( $\sim 0.8$ ). If we analyze all 62 objects, including those with known AGN/QSO emission, we obtain a similar result: in 61% (38/62) of the cases, BCD templates provide a better photometric redshift than either M82 or Arp 220. These results are summarized in Table 2, while Figure 2 shows the distribution of  $z_{\text{phot}} - z_{\text{spec}}$  for different templates. It is clear that the BCD template for NGC 5253 gives a distribution much more peaked around zero.

For this sample of 40 objects, whose SEDs comprise only submillimeter and radio fluxes, the SED that best predicts  $z_{\text{phot}}$  is NGC 5253, with an  $A_V = 10$  mag and a thermal radio spectrum. More than 60% of the radio-identified submillimeter sources are better fit with a flatter radio spectrum ( $-0.1 \leq \alpha \leq -0.3$ ) than with the usual steeper spectrum ( $\alpha \approx -0.7$ ) observed in virtually all evolved starbursts (Condon 1992).

## 5. CONCLUSIONS

Active BCDs may be characterized by star formation modes similar to those in high- $z$  starburst galaxies, specifically for the efficiency and compactness of the star formation. We have compared the observed SEDs of spectroscopically identified submillimeter galaxies with BCD SED templates, for both a small sample of submillimeter galaxies with sensitive *Spitzer* observations and a larger sample of submillimeter galaxies with only radio (and submillimeter) data. In most cases we find that BCD galaxies match the SED observed in distant submillimeter galaxies better than the more widely adopted templates of standard starbursts (M82 and Arp 220). If the BCD templates are used for the photometric redshift technique, then the inferred  $z_{\text{phot}}$  are significantly closer to the actual spectroscopic redshifts than what is inferred by using the templates of M82 or Arp 220. Our results strongly suggest that the dusty embedded star clusters in BCD galaxies provide superior templates to derive the photometric redshift of distant submillimeter, starburst galaxies that may be too faint to be identified spectroscopically.

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