A MULTI-WAVELENGTH VIEW OF THE STAR FORMATION ACTIVITY AT $z \sim 3$

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ABSTRACT

We present a multi-wavelength, UV-to-radio analysis for a sample of massive ($M_\ast \sim 10^{10} M_\odot$) IRAC- and MIPS 24 $\mu$m detected Lyman break galaxies (LBGs) with spectroscopic redshifts $z \sim 3$ in the GOODS-North field. For LBGs without individual 24 $\mu$m detections, we employ stacking techniques at 24 $\mu$m, 1.1 mm, and 1.4 GHz to construct the average UV-to-radio spectral energy distribution and find it to be consistent with that of a luminous infrared galaxy with $L_{IR} = 4.5^{+1.5}_{-1.1} \times 10^{11} L_\odot$ and a specific star formation rate of 4.3 Gyr$^{-1}$ that corresponds to a mass doubling time $\sim 230$ Myr. On the other hand, when considering the 24 $\mu$m detected LBGs we find among them galaxies with $L_{IR} > 10^{12} L_\odot$, indicating that the space density of $z \sim 3$ UV-selected ultra-luminous infrared galaxies (ULIRGs) is $\sim (1.5 \pm 0.5) \times 10^{-5}$ Mpc$^{-3}$. We compare measurements of star formation rates from data at different wavelengths and find that there is tight correlation (Kendall’s $\tau > 99.7\%$) and excellent agreement between the values derived from dust-corrected UV, mid-IR, millimeter, and radio data for the whole range of $L_{IR}$ up to $L_{IR} \sim 10^{13} L_\odot$. This range is greater than that for which the correlation is known to hold at $z \sim 2$, possibly due to the lack of significant contribution from polycyclic aromatic hydrocarbons to the 24 $\mu$m flux at $z \sim 3$. The fact that this agreement is observed for galaxies with $L_{IR} > 10^{12} L_\odot$ suggests that star formation in UV-selected ULIRGs, as well as the bulk of star formation activity at this redshift, is not embedded in optically thick regions as seen in local ULIRGs and submillimeter-selected galaxies at $z = 2$.

Key words: cosmology: observations – galaxies: evolution – galaxies: high-redshift – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

One of the most fundamental quantities needed for our understanding of the nature and evolution of galaxies is the star formation rate (SFR). To get reliable and meaningful estimates of the SFR for galaxies at high redshift, one needs a well-defined sample of objects, coupled with multi-wavelength data that can provide a thorough and comprehensive investigation.

One of the most successful methods of detecting high-$z$ star-forming galaxies is the Lyman break technique, pioneered by Steidel et al. (1996, 2003). This technique has revealed a wealth of Lyman break galaxies (LBGs) at $z \sim 3$, now comprising an impressive catalog of thousands of star-forming galaxies at this redshift. Multi-wavelength studies of LBGs have provided extensive information on various physical properties of these objects. In particular, measurements at near-infrared wavelengths and at 3.6–8 $\mu$m from the Spitzer Space Telescope Infrared Array Camera (IRAC) instrument indicate that their stellar masses are typically $10^{9}–10^{11} M_\odot$ (e.g., Shapley et al. 2001; Papovich et al. 2001; Magdis et al. 2010).

The dust content and the SFR of LBGs at $z \approx 3$ are still poorly constrained. For their siblings at lower redshift, $z \sim 2$, Reddy & Steidel (2004) and Reddy et al. (2006), using multi-wavelength data ranging from X-rays to radio, have reported that UV can be a reliable SFR indicator if corrected for dust attenuation by an average factor between 4.4 and 5.1. The validity of the UV as a robust SFR indicator has also been presented by Daddi et al. (2005, 2007) for a sample of near-infrared-selected galaxies at $1.5 < z < 2.5$ identified using the BzK technique (see also Dannerbauer et al. 2006). A similar multi-wavelength study for the $z \sim 3$ LBGs, though, is still needed.

In this paper, we make use of the unique compilation of multi-wavelength data on the Great Observatories Origins Deep Survey North field (GOODS-N) to explore the SFR and the infrared luminosities ($L_{IR}$) of $z \sim 3$ LBGs. Our aim is to fully characterize the spectral energy distribution (SED) of a typical LBG from rest-frame UV to radio wavelengths, to compare different tracers of star formation, and to test whether the UV can provide a reliable measurement of star formation at $z \sim 3$. In this paper we adopt a $\Lambda$ cold dark matter (ΛCDM) cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$, while the magnitudes presented in this work are all in the AB magnitude system.

2. THE LBG SAMPLE AND DATA SETS

2.1. Rest-frame UV Data

In this study, we selected 69 LBGs in the northern field of the GOODS. Their original selection was based on their optical colors ($U_n,G,R$) to $R = 25.5$ by Steidel et al. (2003) and subsequent optical spectroscopy (Steidel et al. 2003; Reddy et al. 2005) has confirmed their high redshift nature with a median $z = 2.95$. Optical spectroscopy also has been used to determine the absence of active galactic nucleus (AGN) signatures (i.e., strong high ionization emission lines) in their rest-frame UV spectrum although a deeply obscured AGN cannot be ruled out from these data. We also use BViz data obtained from
the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST; Giavalisco et al. 2004).

2.2. IRAC and MIPS 24 μm Data

Rest-frame NIR identification and IRAC photometry (5σ, $f_{3.6} = 0.21$ μJy) of the LBGs in our sample have been presented by Magdis et al. (2008, 2010), who also showed that their mid-IR colors are consistent with those of star-forming galaxies at $z \sim 3$. Here, we focus on the 49 LBGs with at least one IRAC detection ([3.6]_{AB} < 25.0) in order to place a lower mass limit of $M_* \sim 10^{10} M_\odot$ (Magdis et al. 2010) and facilitate a robust investigation of their properties and their average SED. We note that the $R$ magnitude limit of our sample, ($R_{AB} < 25.5$), corresponds to $L_{UV} > 1.8 \times L^*_{z=3} (M^*_R = -21$; Steidel et al. 1999).

We matched our sample with a GOODS-N 24 μm catalog (5σ $\sim 20$ μJy, translated to SFR $\approx 350 M_\odot$ yr$^{-1}$ or $L_{IR} \approx 2 \times 10^{12} L_\odot$ based on Chary & Elbaz (2001) models at $z = 3$) produced by the GOODS team (M. Dickinson et al. 2010, in preparation), and searched for counterparts within a 2″ diameter separation centered on the optical position. We identify nine LBGs and we add another five 24 μm detected LBGs in the extended growth strip (EGS; 5σ $\sim 70$ μJy) by Rigopoulou et al. (2006) to increase our 24 μm detected sample. We note that the original optical selection of these extra five EGS MIPS-selected LBGs is identical to that of the GOODS-N sample, so they share similar UV properties and including them in our sample does not introduce any bias. Henceforth, we will refer to LBGs that are individually detected at 24 μm as MIPS–LBGs (14 objects), and those that are not as IRAC–LBGs (40 objects).

In practice, all MIPS–LBGs are also detected in all four IRAC bands. The redshift range of the two samples is 2.63 < $z$ < 3.41 (IRAC–LBGs) and 2.60 < $z$ < 3.31 (MIPS–LBGs) following a similar distribution. The median redshift of the MIPS–IRAC–LBGs is 2.92 and 2.98, respectively.

For the 24 μm-undetected IRAC–LBGs in GOODS-N we employed median stacking analysis. We first subtracted all detected sources using the point-spread function (PSF) used for the source extraction, and cut sub-images centered at the optical position of each undetected LBG. To avoid contaminating the stacked signal from residuals, we only added galaxies to the stack if there were no bright MIPS sources within ~4″ of those galaxies. Then a stacked flux was measured in a manner similar to the measurement of the detected MIPS sources. The final stacked image at the position of the IRAC–LBGs is shown in Figure 1(a). To quantify the error of our measurement we stacked 50,000 times along with the best Gaussian fit (rms $\approx 1.04$ μJy). The red line denotes the flux measurement of the stacking at the position IRAC–LBGs. This indicates a $\sim 7.9 \sigma$ detection at the stacked position of the LBGs. (e) Stacking at 1.1 mm. Same as (d) but for the Aztec 1.1 mm and for 5000 stackings. This figure indicates a $\sim 3.7 \sigma$ detection at the stacked position of the IR–LBGs.

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

Figure 1. Stacked image at 24 μm (a), 1.1 mm (b), and radio 1.4 GHz (c) of IRAC–LBGs. (d) Stacking simulations at 24 μm. Distribution of the measured fluxes derived from 50,000 stackings at 40 random positions along with the best Gaussian fit (rms = 1.04 μJy). The red line denotes the flux measurement of the stacking at the position IRAC–LBGs. This indicates a $\sim 7.9 \sigma$ detection at the stacked position of the LBGs. (e) Stacking at 1.1 mm. Same as (d) but for the Aztec 1.1 mm and for 5000 stackings. This figure indicates a $\sim 3.7 \sigma$ detection at the stacked position of the IR–LBGs.

Previous studies have demonstrated that MIPS–LBGs are, on average, more massive, relatively older, and dustier compared to LBGs that are undetected at 24 μm (e.g., Rigopoulou et al. 2006; Magdis et al. 2010). In the rest of this paper we study the IRAC–LBGs and MIPS–LBGs separately to enable a comparison between the two sub-populations of LBGs and
examine our results as a function of $L_{\text{IR}}$ and dust extinction. For our statistical analysis we always refer to median values.

2.3. Aztec 1.1 mm Data

Recently, a deep ($\sigma \sim 0.96$–1.16 mJy beam$^{-1}$) and uniform 1.1 mm survey of the GOODS-N field with Aztec (Wilson et al. 2008) was conducted on the James Clerk Maxwell Telescope. Matching our sample with the catalogs published by Perera et al. (2008) and Chapin et al. (2009), returned no individual detection down to 3.75$\sigma$ level. Since none of our LBGs is individually detected, we used the publicly available maps to do stacking. We perform median stacking at the positions of IRAC–LBGs after rejecting two of them that are separated by less than an Aztec beam half-width (9$''$) from any known Aztec detection (Figure 1(b)). The median flux that we recover for the IRAC–LBGs is $f_{1.1 \text{ mm}} = 0.41 \pm 0.11$ mJy (3.7$\sigma$). The robustness of this flux was also tested by the same bootstrapping. Finally, stacking at the positions of the seven GOODS-N MIPS–LBGs (two were rejected due to confusion) returned no detection indicating a 4$\sigma$ upper flux density limit of 1.08 mJy.

2.4. VLA 1.4 GHz Radio Data

We use a new deep 20 cm (1.4 GHz) imaging of the GOODS-N field obtained at the VLA in ABCD configurations (Morrison et al. 2010). Previous observations by Richards (2000) contained 40 usable hours of A-array data which were supplemented with 125 hr yielding an rms of 3.9 $\mu$Jy beam$^{-1}$ near the phase center. We matched our LBG sample to the 5$\sigma$ radio catalog (Morrison et al. 2010) and identified one MIPS–LBG, HDFN-M23 with a flux $S_{1.4 \text{ GHz}} = 21.19 \pm 4.2 \mu$Jy ($z = 3.21$).

In order to reach deeper radio flux densities, we stacked individually undetected LBG sources using the following technique. Using a primary beam corrected radio image, we made 100 pixel $\times$ 100 pixel sub-images centered on the LBG positions. The exported FITS files were then stacked using the Terapix co-add software (Bertin et al. 2002). The stacking used the pixel reference frame and the resulting stacked image was median combined. We stacked separately MIPS– and IRAC–LBGs and derived a median flux density of $8.5 \pm 2.2 \mu$Jy and $3.6 \pm 0.8 \mu$Jy, respectively. The stacked image of the IRAC–LBGs is shown in Figure 1(c).

3. SFR INDICATORS

**UV SFR estimates.** To determine the UV-corrected SFR ($\text{SFR}_{\text{UV,corr}}$), we use the GOODS ACS photometric catalog retrieved from MAST STScI (Version v2.0). At $z \sim 3$ the observed $V$, $I$, and $z$ bands correspond to rest frame 1500 Å, 2000 Å, and 2400 Å, respectively, allowing a robust estimate of the $\beta$ slope. We use dust-free models of continuous SFR, solar metallicity, age $t_{\text{age}} = 100$ Myr, and Salpeter IMF, generated with the new code of S. Charlot & G. Bruzual (2007, private communication) (CB07) to fit the SED of each individual LBG after correcting for reddening using the Calzetti et al. (2000) attenuation law and correcting for the intergalactic medium (IGM) attenuation using the prescription of Madau (1995). From the best-fit model, we derive $E(B-V)$ values and apply a $K$-correction to infer the observed and subsequently the intrinsic flux density at 1500 Å in the rest frame. The average $E(B-V)$ value is 0.16 ($A_V = 4.6$) and agrees well with previous studies (i.e., Shapley et al. 2001). The adopted CB07 models yield a relation between the SFR and the monochromatic 1500 Å luminosity given by

$$\text{SFR}(M_{\odot}yr^{-1}) = L_{1500\text{Å}} \text{(erg s}^{-1}\text{Hz}^{-1})/(8.85 \times 10^{27}).$$ (1)

Using extinction-corrected $L_{1500\text{Å}}$ in Equation (1) provides an estimate of the total SFR ($\text{SFR}_{\text{UV,uncorrected}}$). The total SFR can be considered as the sum of an unobscured component ($\text{SFR}_{\text{UV,uncorrected}}$), which can be computed from Equation (1) by using the observed $L_{1500\text{Å}}$ and an obscured component ($\text{SFR}_{\text{obs}}$), corresponding to the energy absorbed by dust. This absorbed energy is in turn reradiated at mid- and far-infrared wavelengths, $\text{SFR}_{\text{obs}} = \text{SFR}_{\text{IR}}$, and it is this latter quantity that we will infer from the mid- and far-infrared data. Therefore, we may write

$$\text{SFR}_{\text{UV,corrected}} = \text{SFR}_{\text{IR}} + \text{SFR}_{\text{UV,uncorrected}}.$$ (2)

24 $\mu$m, 1.1 mm, 1.4 GHz radio SFR, and $L_{\text{IR}}$ estimates. To convert 24 $\mu$m and Aztec fluxes to total (8–1000 $\mu$m) $L_{\text{IR}}$, we use the luminosity-dependent SED library of Chary & Elbaz (2001) (CE01), while for comparison we also consider the Dale & Helou (2002) (DH02) models (with luminosities normalized as described by Marcillac et al. 2006) and SED templates of Arp220 and M82. This is done by interpolating $L_{\text{IR}}$ over the template SEDs, sorting the value of $L_{\text{IR}}$ that corresponds to the observed 24 $\mu$m flux density. For the radio-based $L_{\text{IR}}$ estimates, we first derive the observed radio luminosities and then assume a radio spectral index of $\alpha = -0.8$ to get the rest-frame 1.4 GHz radio luminosities. Then we use the local radio–IR correlation (Condon 1992) to determine $L_{\text{IR}}$:

$$L_{\text{IR}}/L_{\odot} = 3.5 \times 10^{-12} L_{1.4 \text{ GHz}} (\text{W} \text{ Hz}^{-1}).$$ (3)

The $L_{\text{IR}}$ is subsequently converted to $\text{SFR}_{\text{IR}}$ using Kennicutt (1998):

$$\text{SFR}_{\text{radio}}(M_{\odot} \text{yr}^{-1}) = 1.73 \times 10^{-10} L_{\text{IR}}(L_{\odot}).$$ (4)

4. COMPARISON OF UV, MID-IR, MILLIMETER, AND RADIO SFR/$L_{\text{IR}}$ ESTIMATES

4.1. UV versus 24 $\mu$m

We first compare the SFR and $L_{\text{IR}}$ derived from UV and mid-IR in Figure 2, where we also show the expected correlation based on the CE01, DH02, Arp220, and M82 templates. For the IRAC–LBGs, we use the $L_{\text{IR}}$ derived from the stacking analysis, while for the rest we use the one derived from their measured 24 $\mu$m flux densities. It is evident that between UV and 24 $\mu$m derived luminosities based on CE01 and DH02 templates, there is a close agreement which for the case of the latter templates is more prominent. The Kendall’s $\tau$ test detects a correlation at a >99.7% confidence level, that holds up to $L_{\text{IR}} \sim 10^{13} L_{\odot}$, where the two estimates appear to deviate. The two galaxies with the largest 24 $\mu$m derived $L_{\text{IR}}$ and with the largest deviations between the UV and 24 $\mu$m derived SFR, are also detected at 1.2 mm by MAMBO (Rigopoulou et al. 2010), and are therefore members of the SMG population for which such a trend is known to exist either due to star formation embedded in optically thick regions or due to contribution from an AGN to the mid-IR output, or both (e.g., Chapman et al. 2005; Chapman & Casey 2009; Pope et al. 2008). We also note that for these two galaxies, a scaled-up M82 template provides a good agreement between the UV and 24 $\mu$m derived $L_{\text{IR}}$. 


A similar correlation between UV- and mid-IR-derived SFRs has also been observed at $z \sim 2$ for BzK (Daddi et al. 2007) and BX/BM (Reddy et al. 2006) galaxies with the two estimates though deviating at lower luminosities ($\sim 3 \times 10^{12} L_\odot$) when compared to our findings at $z \sim 3$. It is therefore indicated that the UV-24 $\mu$m correlation at $z \sim 3$ is better than that found at $z \sim 2$. One possible explanation could reside in the contribution of polycyclic aromatic hydrocarbon (PAH) features in the observed mid-IR flux. While evidence was found that PAHs are enhanced in $z \sim 2$ star-forming galaxies (Murphy et al. 2009) with respect to local galaxies, this may not be the case anymore at $z \sim 3$ when galaxies were less metal rich and PAHs less abundant. We note that while for $z \sim 2$ galaxies the 24 $\mu$m is centered at the PAH emission, at $z \sim 3$ the band traces only the 6.2 $\mu$m and part of the 7.7 $\mu$m PAH feature. This shift though cannot fully explain our findings as for a M82-like object, the contribution of the PAHs to the 24 $\mu$m flux density is comparable at the two redshifts (50%–70%). Alternatively, it could be argued that the mid-IR radiation of our sample is less polluted by the emission of hot dust heated by an AGN, which could be a natural result of the rapid drop of the number density of AGNs above $z \sim 2$ (Wall et al. 2005).

4.2. UV versus Radio and 1.1 mm

One independent way to check the UV SFR estimates is to compare them against radio observations. In Figure 3, we plot the SFR estimates based on the radio fluxes and the UV-corrected for dust extinction for three samples: HDFN-M23 which is individually detected in the radio map, the stacked flux of radio-undetected MIPS–LBGs, and the stacked flux of radio-undetected IRAC–LBGs. We see that there is an excellent agreement between the radio and UV estimates, testifying to the validity of UV as an SFR indicator for UV-selected galaxies at $z \sim 3$. The corresponding SFRs derived from UV (and radio) are $90_{-30}^{+35} M_\odot$ yr$^{-1}$ (and 96 $\pm$ 32 $M_\odot$ yr$^{-1}$) for the IRAC–LBGs, $250_{-80}^{+35} M_\odot$ yr$^{-1}$ (and 280 $\pm$ 85 $M_\odot$ yr$^{-1}$) for the MIPS–LBGs, and $808 M_\odot$ yr$^{-1}$ (and 870 $\pm$ 200 $M_\odot$ yr$^{-1}$) for HDFN-M23. A similar study by Carilli et al. (2008), comparing radio and UV data for $z \sim 3$ LBGs in COSMOS, inferred an average UV attenuation factor of $\sim 1.8$, smaller than the average value of $\sim 5$ derived here and in other studies (e.g., Reddy & Steidel 2004; Reddy et al. 2006). We argue that the discrepancy arises from the fact that we focus on massive (dusty) LBGs with robust spectroscopic redshifts and compute dust attenuation on an object-by-object basis from the UV spectral slopes, whereas Carilli et al. primarily use photometric redshifts, infer only an average attenuation, and do not consider a mass-limited sample. Finally, we explore the relation between the UV and the $L_{24\mu}$ as derived from millimeter. Following the same prescription as above, we convert the millimeter-stacked flux, the IRAC–LBGs, and find it to be in agreement with the $L_{24\mu}$ derived from the UV. The two corresponding values are $(6.2 \pm 3) \times 10^{11} L_\odot$ (mm) and $5.1 \times 10^{11} L_\odot$ (UV). Converting the stacked millimeter value to SCUBA850 $\mu$m by using the formula presented by Ivison et al. (2005) we get $S_{850} = 0.85 \pm 0.27$ mJy indicating that IRAC–LBGs emit at the sub-mJy level at 850 $\mu$m. We note that similar to the SMGs, where UV is an unreliable indicator of SFR, there is evidence of existing optically thick star-forming regions in the case of submillimeter-detected LBGs (e.g., Rigopoulou et al. 2010; Chapman & Casey 2009).

5. DISCUSSION

Considering the median fluxes of the IRAC–LBGs for the rest-frame UV to NIR (i.e., $U_r$ to 8.0 $\mu$m) and stacked fluxes at 24 $\mu$m, 1.1 mm, and 1.4 GHz, we construct the average SED of a typical (24 $\mu$m faint) IRAC–LBG. We fit the rest-frame
UV to NIR with model SEDs generated using the CB07 code, and the mid-IR to radio with CE01 templates. The photometric points along with the best-fit model are shown in Figure 4. The best-fit CB07 model indicates an average stellar mass of $M_*(\sim 2.2 \times 10^{10} M_\odot)$ and an average SFR $\sim 85 M_\odot$ yr$^{-1}$. Using this mass estimate and the SFR derived from our multi-wavelength analysis we derive a specific SFR (SSFR, defined as SFR/$M_*$) $\sim 4.3$ Gyr$^{-1}$, corresponding to a mass doubling time of $\sim 230$ Myr. This value is very close to the one presented by Magdis et al. (2010) (4.5 Gyr$^{-1}$) and is larger than that found at lower and higher redshifts, reinforcing their argument that the evolution of the SSFR peaks at $z \sim 3$. Based on CE01 models we find that the average IRAC–LBG is a luminous infrared galaxy (LIRG) with $L_{IR} = 4.5^{+1.5}_{-1.3} \times 10^{11} L_\odot$. We note that $L_{IR}$ corresponds to a typical dust temperature $T_d = 35$ K, based on $T_d$ measurements of local LIRGs (Yang & Phillips 2007).

On the other hand, MIPS–LBGs have higher luminosities, indicating that ultra-luminous infrared galaxies (ULIRGs) are present among the UV-selected galaxies at $z \sim 3$. For instance, HDFN-M23, which was individually detected in the radio, has $L_{IR} \sim 5(\pm 2) \times 10^{12} L_\odot$. We calculate the comoving volume for the redshift range of our sample ($2.5 < z < 3.5$) and find that the space density of ULIRGs (based on UV L$_{IR}$) LBGs is $\sim 1.5 \pm 0.5 \times 10^{-5}$ Mpc$^{-3}$. This is a factor of $\sim 10$ smaller than the space density of the $z \sim 2$ BzK-selected ULIRGs (Daddi et al. 2007). We note that the UV selection is likely to miss more obscured, UV faint ULIRGs as our sample is limited to $R_{AB} < 25.5$ while, for example, an Arp220-like object at $z \sim 3$ would have $R_{AB} \sim 26.9$.

The good agreement between SFR indicators that are affected by dust extinction (UV) or not (MIR, millimeter, radio) suggests that the bulk of the star formation activity in massive UV-selected galaxies takes place in optically thin regions. Since by focusing on the massive LBGs we also select those that are most affected by dust extinction (e.g., Magdis et al. 2010), it is reasonable to extend this result to the whole population of UV galaxies including the less massive, less dusty LBGs. Furthermore, the fact that the agreement holds even for the case of the most massive, dusty, 24 $\mu$m detected LBGs with $L_{IR} > 10^{12} L_\odot$ indicates that UV-selected ULIRGs at $z = 3$ are transparent to UV light, meaning that we can estimate its SFR given its rest-frame UV $1500$ Å luminosity and UV slope, contrary to the local ULIRGs and $z \sim 2$ SMGs. Similar results have been reached by Reddy et al. (2006) for UV-selected and by Daddi et al. (2007) for BzK-selected $z \sim 2$ LIRGs and ULIRGs. Both studies find that galaxies of a given bolometric luminosity are on average a factor of 8–10 less dust obscured at $z \sim 2$ than at the present epoch. The fact that our study suggests that at $z \sim 3$ ULIRGs are optically thin at even higher $L_{IR}$ than that at $z \sim 2$ indicates even less obscuration at $z \sim 3$ confirming the trend between galaxies at $z = 0, z = 1$, and $z \sim 3$ (Adelberger & Steidel 2000). This could plausibly be explained as a result of increasing dust-to-gas ratios as we move from the high-$z$ to the present universe. As galaxies evolve, they convert gas into stars which in turn enrich the interstellar medium with dust. If the dust distribution becomes more compact with time (assuming mergers that drive dust and gas to the center of the galaxy) the overall result would be an increase of the dust column density toward star-forming regions making ULIRGs progressively optically opaque at later epochs.

To put constraints on the number of the cosmic star formation activity at $z = 3$, we should also consider the missing fraction of star formation embedded in optically thick regions that takes place in galaxies not selected in UV. On the other hand, there is evidence of decreasing obscuration with increasing redshift for a given $L_{IR}$ (e.g., Reddy et al. 2008), pointing toward less optically thick star formation at higher redshifts. Combining the above with the fact that the bulk of the currently known SMGs are at $z \sim 2.2$ (Chapman et al. 2005), we can assume that at $z = 3$ the contribution of the SMGs to the total SFR density is not
dominant, and hence locate the census of high-\(z\) star formation in optically thin regions. We stress that such a scenario cannot be confirmed based solely on our sample, as it has been shown that the Lyman break technique can miss a large fraction of massive (dusty) galaxies at high-\(z\) (e.g., Daddi et al. 2004; Van Dokkum et al. 2006).

Further insights into the far-IR properties of the LBGs, such as dust temperature and dust mass will be provided by deep surveys with the Photodetector Array Camera & Spectrometer (PACS; 70, 100, 160 \(\mu\)m) and the Photometric Imaging REceiver (SPIRE; 250, 350–500 \(\mu\)m) on board the Herschel Space Observatory (HSO). Based on the average spectrum of Figure 4, the predicted flux densities in the HSO bands of a typical IRAC-detected LBG are \(f_{100} = 0.13\) mJy, \(f_{160} = 0.47\) mJy, \(f_{250} = 1.18\) mJy, \(f_{350} = 1.52\) mJy, and \(f_{500} = 1.22\) mJy.

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