A FIRST GLIMPSE INTO THE FAR-IR PROPERTIES OF HIGH-\(z\) UV-SELECTED GALAXIES: HERSCHEL/PACS OBSERVATIONS OF \(z \sim 3\) LBGs

G. E. Magdis\(^1\), D. Elbaz\(^1\), H. S. Hwang\(^1\), E. Daddi\(^1\), D. Rigopoulou\(^2\), B. Altieri\(^3\), P. Andreani\(^4\), H. Aussel\(^1\), S. Berta\(^5\), A. Cava\(^6\), A. Bongiovanni\(^6\), J. Cepa\(^6\), A. Cimatti\(^6\), M. Dickinson\(^6\), H. Dominguez\(^6\), N. Förster Schreiber\(^7\), R. Genzel\(^8\), J.-S. Huang\(^9\), D. Lutz\(^9\), R. Maiolino\(^10\), B. Magnelli\(^10\), G. E. Morrison\(^11,13\), R. Nordon\(^10\), A. M. Pérez García\(^6\), A. Poglitsch\(^5\), P. Popesso\(^5\), F. Pozzi\(^11\), L. Riguccini\(^5\), G. Rodighiero\(^5\), A. Santonge\(^5\), P. Santini\(^11\), M. Sanchez-Portal\(^5\), L. Shao\(^5\), E. Sturm\(^5\), L. Tacconi\(^8\), and I. Valtchanov\(^14\)

1 CEA, Laboratoire AIM, Irfu/SAp, F-91191 GIF-sur-Yvette, France
2 Department of Astrophysics, Oxford University, Keble Road, Oxford OX1 3RH, UK
3 European Space Astronomy Centre, Villanueva del Castillo, Spain
4 ESO, Karl-Schwarzschild-Str, 2, D-85748 Garching, Germany
5 Max-Planck-Institut für Extraterrestrische Physik (MPE), Postfach 1312, 85741 Garching, Germany
6 Dipartimento di Astronomia, Università di Padova, Vicolo dell’Osservatorio 3, 35122 Padova, Italy
7 NOAO, 950 N. Cherry Avenue, Tucson, AZ 85719, USA
8 INAF-Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy
9 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
10 INAF-Osservatorio Astronomico di Roma, via di Frascati 33, 00040 Monte Porzio Catone, Italy
11 Institute for Astronomy, University of Hawaii, Honolulu, HI 96822, USA
12 Canada–France–Hawaii Telescope, Kamuela, HI 96743, USA
13 European Space Astronomy Centre, Villafranca del Castillo Satellite Tracking Station, Madrid, Spain
14 Herschel Science Centre, European Space Astronomy Centre, Villafranca del Castillo Satellite Tracking Station, Madrid, Spain

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ABSTRACT

We present first insights into the far-IR properties for a sample of IRAC and MIPS 24 \(\mu\)m detected Lyman break galaxies (LBGs) at \(z \sim 3\), as derived from observations in the northern field of the Great Observatories Origins Survey (GOODS-N) carried out with the PACS instrument on board the Herschel Space Observatory. Although none of our galaxies are detected by Herschel, we employ a stacking technique to construct, for the first time, the average spectral energy distribution (SED) of infrared luminous LBGs from UV to radio wavelengths. We derive a median IR luminosity of \(L_{IR} = 1.6 \times 10^{12} L_{\odot}\), placing the population in the class of ultra-luminous infrared galaxies (ULIRGs). Complementing our study with existing multi-wavelength data, we put constraints on the dust temperature of the population and find that for their average SED, explains the marginal detection of LBGs in current submillimeter surveys and suggests that these latter studies introduce a bias toward the detection of colder ULIRGs in the high-\(z\) universe, while missing high-\(z\) ULIRGs with warmer dust.

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

Online-only material: color figures

1. INTRODUCTION

Lyman break galaxies (LBGs) represent a significant fraction of \(z \sim 3\) star-forming galaxies that have been discovered up to now. Since LBGs are the most common population at this epoch, investigating their properties is crucial to enhance our view of the early universe. A large number of multi-wavelength studies, spanning from X-rays to radio, have characterized the nature of the population. One recent advance into our understanding of this population was provided by the Infrared Array Camera (IRAC), the Multi-band Imaging Photometer (MIPS), and the Infrared Spectrograph (IRS) on board the Spitzer Space Telescope (Spitzer). In particular, IRAC measurements at rest-frame near-infrared wavelengths (3.6–8 \(\mu\)m) indicate that their stellar masses are typically \(10^9–10^{11} M_{\odot}\) (e.g., Magdis et al. 2008, 2010b) while the detection of a fraction (~20%) of these UV-selected galaxies at MIPS 24 \(\mu\)m unveiled the sub-population of the infrared luminous LBGs (Huang et al. 2005; Rigopoulou et al. 2006). Subsequent follow-up IRS spectroscopy of MIPS-detected LBGs revealed prominent polycyclic aromatic hydrocarbon (PAH) features in their mid-IR spectrum, providing evidence for the existence of significant amounts of dust and showing that they are mainly powered by star formation rather than an active galactic nucleus (AGN; Huang et al. 2007; Rigopoulou et al. 2010).

The star formation rate (SFR) of MIPS-detected LBGs has been studied in detail by Magdis et al. (2010a), where they found that UV, mid-IR, and radio measurements of the SFR for UV-selected galaxies are in good agreement, indicating an average (SFR) = 250 \(M_{\odot}\) yr\(^{-1}\). This SFR, along with the fact that these galaxies contain considerable amounts of dust as indicated by their mid-IR emission, suggests that MIPS-LBGs should be detectable at submillimeter wavelengths. Although the first attempts to detect far-IR counterparts were not successful (e.g., Chapman et al. 2000), recently there has been significant progress in this front. Chapman & Casey (2009) reported the SCUBA 850 \(\mu\)m submillimeter detection of Westphal-MM8, while Rigopoulou et al. (2010) reported MAMBO 1.2 mm
detections of a further two LBGs, EGS-D49 and EGS-M28, selected based on their strong MIPS 24 μm emission. In addition to those, two more lensed LBGs have been detected in the submillimeter by Baker et al. (2001; MS1512-cB58) and Siana et al. (2009; Cosmic Eye). Despite these promising detections though, the FIR properties of LBGs still remain elusive.

In this Letter, we use observations of the northern field of the Great Observatories Origins Survey (GOODS-N) obtained by Photoconductor Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) on board the Herschel Space Observatory (Pilbratt et al. 2010). We complement our study with multi-wavelength data and we aim to get a first insight into the FIR properties of a sample of MIPS 24 μm detected LBGs, construct the average spectral energy distribution (SED) of the population, derive estimates of their dust temperature ($T_d$), and compare their properties to those of sub-millimeter galaxies (SMGs).

The Herschel data used in this study are part of the Herschel Science Demonstration Phase of the PACS Evolutionary Probe (PEP; PI: Lutz) program. Throughout this Letter, we assume $\Omega_m = 0.3$, $H_0 = 71 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, and $\Omega_\Lambda = 0.7$.

2. SAMPLE SELECTION AND HERSCHEL OBSERVATIONS

GOODS-North was observed by PACS at 100 and 160 μm in the framework of the Guaranteed Time Key Program, PACS Evolutionary Probe (PEP). The area covered by PACS was $10' \times 15'$ in a total exposure time of 30 hr and an average integration time of $\sim 2.5 \, \text{s pixel}^{-1}$. For source extraction, two independent methods were employed: the traditional blind source extraction that was performed by using the Starfinder point-spread function (PSF)-fitting code (Dionati et al. 2000) and a guided extraction using 24 μm priors. In both methods, PSFs were extracted from the final science maps and were subsequently used for a PSF-fitting photometric analysis. Flux uncertainties were obtained by Monte Carlo simulations, adding fake sources in the real maps. The measured 1σ noise is 1.00 mJy at 100 μm and 1.90 mJy at 160 μm. For more details, we refer the reader to the appendix of Berta et al. (2010).

Our sample of LBGs is identical to the one studied by Magdis et al. (2010a), and we refer the reader to this paper for a detailed description. In brief, we consider 49 IRAC-detected ([3.6]$_{AB} < 25.0$ or 0.36 μJy) LBGs in GOODS-N that have originally been optically selected ($U, G, R < 25.5$) by Steidel et al. (2003). All galaxies in our sample have spectroscopic redshift (median $z = 2.95$) derived by optical spectroscopy that has also been used to determine the absence of AGN signatures (i.e., strong high-ionization emission lines) in their rest-frame UV spectrum (Steidel et al. 2003; Shapley et al. 2003). Among the original sample, nine LBGs are also detected at MIPS 24 μm ($5\sigma \sim 20 \, \mu\text{Jy}$) with a median 24 μm flux density $f_{24} = 31.2 \, \mu\text{Jy}$. Henceforth, we will refer to these LBGs as the MIPS-LBGs while to the remaining (40) as IRAC-LBGs. IRAC photometry for these objects is provided in Magdis et al. (2010b), while an analysis of MIPS 24 μm data is described in Magdis et al. (2010a). Matching our sample with the 100 and 160 μm blind and prior catalogs returned no individual detections at the 3σ level (3 mJy and $\sim 5$ mJy, respectively). Since none of our LBGs are individually detected we use the residual maps to do stacking. On stacking we first considered the sample of MIPS-LBGs. We employed median stacking analysis, cutting sub-images of the residual maps centered at the optical position of each undetected LBG. The residual maps were created by Starfinder by subtracting all individually detected sources down to 3σ. To avoid contaminating the stacked signal from residuals, we only added galaxies to the stack if there were no bright sources within $\sim 4' (100 \, \mu\text{m})$ and $\sim 6' (160 \, \mu\text{m}).$ Then a stacked flux was measured in a manner similar to the measurement of the detected PACS sources. To quantify the error of our measurement, we stacked at nine random positions and repeated it 50,000 times. The 1σ of the distribution of the derived fluxes was adopted as the uncertainty of our measurement. Stacking at 100 μm returned no detection ($f_{100} = 0.47 \pm 0.36 \, \text{mJy}$) indicating a 3σ upper limit of $f_{100} < 1.1 \, \text{mJy}$, while at 160 μm we recovered a median flux density $f_{160} = 2.21 \pm 0.52 \, \text{mJy}$ (S/N $\sim 4.2$) for the MIPS-LBGs. The final 160 μm stacked image is shown in Figure 1 along with the distribution of the fluxes that correspond to random stacked positions. This distribution indicates the probability to recover a stacked flux density $f_{160} > 4.2 \, \text{mJy}$ by chance, which is $2.31 \times 10^{-5}$. Stacking the whole sample of LBGs, or just the IRAC-LBGs alone, returned no detection in either PACS band. For the IRAC-LBGs, we determine a 3σ upper limit of $f_{100} < 0.47 \, \text{mJy}$ and $f_{160} < 0.79 \, \text{mJy}$ while the actual fluxes that correspond to the stacked images are $f_{100} = 0.21 \pm 0.16 \, \text{mJy}$ and $f_{160} = 0.32 \pm 0.26 \, \text{mJy}$.

![Figure 1](image-url)

**Figure 1.** Left: PACS-160 μm stacked image (130" × 130") of nine MIPS 24 μm detected LBGs in GOODS-N. Right: stacking simulations at 160 μm. Distribution of the measured fluxes derived from 50,000 stackings at nine random positions along with the best Gaussian fit (rms = 0.52 mJy). The red line denotes the flux measurement of the stacking at the position MIPS-LBGs indicating a $\sim 4.2\sigma$ detection. (A color version of this figure is available in the online journal.)
indicating a median nosities are normalized as described by Marcillac et al. (2006). Libraries. For the fitting procedure, we allow for renormalization of the SEDs peak at shorter wavelengths than those of LIRGs. Here, we attempt to put constraints on the peak of the SED and the dust temperature ($T_d$) of LBGs and investigate these parameters as a function of luminosity at $z \sim 3$.

Although ideally such a task requires photometric points close to the peak of the SED of a galaxy (which in this case translates into SPIRE data), here we use PACS 160 μm and AzTEC 1.1 mm flux densities and upper limits, with the advantage of sampling both sides around the peak of the SED. Using 3σ upper limits for the $f_{160}$ of IRAC-LBGs could provide us with an upper limit of the $T_d$ of the sample while 3σ upper limits for the $f_{1.1\text{mm}}$ of the MIPS-LBGs will yield an estimate of a lower limit of the $T_d$ of the sample.

We first employed Monte Carlo simulations to generate 10,000 combinations of 160 μm and 1.1 mm fluxes. For each of the two bands, the simulated fluxes were generated following the flux distribution derived from the stacking simulations and centered on the measured stacked flux. To derive the dust temperature for each of the generated realizations, we used a single-temperature greybody fitting form, $F_{\nu}(\beta) \propto \nu^{\beta} \exp(-\tau_{\nu})$, where $\beta$ is the dust emissivity and $T_d$ is the effective or emission-weighted dust temperature. We fixed the $\beta$ value to 1.5 (Gordon et al. 2010) and considered the median redshifts as representative for each sample ($z = 2.98$ for IRAC-LBGs and $z = 2.92$ for the MIPS-LBGs). The $T_d$ for each realization was then obtained from the best-fit model that was derived based on the minimization of the $\chi^2$ value. Since at 100 μm (rest frame 25 μm) there is a strong contribution of very small grains (VSGs) in the IR emission, $f_{100}$ upper limits were not fitted but they were considered as a sanity check, i.e., that the models do not violate the upper limits. Based on the distribution of the obtained dust temperatures (Figure 3), we derive an upper limit of $T_d = 38.2$ (39.3) K (IRAC-LBGs) and a lower limit of $T_d = 40.1$ (39.9) K (MIPS-LBGs) at a 2σ (3σ) confidence level. The best-fit models that correspond to the 2σ temperature limits are depicted in Figure 4. We note that adopting $\beta = 2.0$ instead of 1.5 would result in a lower dust temperature by 2–3 K.

The above analysis indicates that the dust temperatures of the two samples are different at a 2.6σ confidence level, with MIPS-LBGs having warmer dust. MIPS-LBGs and IRAC-LBGs are objects divided by a threshold in their rest 6 μm emission, which is due to warm, very small grains and/or PAHs. If the presence of warm small grains correlates with the presence of warm larger grains then our result would be an object of selection bias. To explore this possibility, we consider a sample of local ULIRGs with ISO/CAM 6.75 μm and IRAS 60 and 100 μm data (Elbaz et al. 2002). Planning $f_{100}/f_{160}$, which is a dust temperature indicator, against the rest-frame 6.75 μm luminosity (that corresponds to 24 μm emission of $z \sim 3$)
reveals that there is no obvious correlation between 6 μm luminosity and $T_d$. Hence, assuming that this applies for galaxies at $z \sim 3$, it seems that our result is not subject to a selection bias. On the other hand, as we have already shown, MIPS-LBGs are more infrared luminous than IRAC-LBGs with the corresponding infrared luminosities $L_{IR} = 1.6(\pm 0.5) \times 10^{12} L_\odot$ for MIPS-LBGs and $L_{IR} = 4.5(\pm 0.5) \times 10^{11} L_\odot$ for IRAC-LBGs. Therefore, it appears that we observe for the first time the general $L_{IR}-T_d$ trend seen in the local universe (with more luminous galaxies having warmer dust) for UV-selected galaxies at $z \sim 3$.

3.3. Comparison with SMGs

Considering the large SFRs and substantial dust reddening that are inferred for some LBGs and the fact that their spectra exhibit characteristics of local starbursts (Pettini et al. 2001), it is somewhat surprising that there are only few examples of direct submillimeter detection for these galaxies. MIPS-LBGs are the most rapidly star-forming, most luminous, and dustiest galaxies among the high-redshift UV-selected population, and therefore are the best candidates for having far-IR emission that could be detected in current submillimeter surveys. In what follows, we discuss how the current data can shed light on the mystery of this marginal detection of LBGs in submillimeter bands. Based on the average SED of MIPS-LBGs that we presented here, we predict that the flux density of MIPS-LBGs emitted at 850 μm is $f_{850} = 1.1–1.5$ mJy, just below the current confusion limit. It could therefore be suggested that MIPS-LBGs provide a link between SMGs and typical UV-selected LBGs that are faint in the IR. It has also been speculated that the fact that LBGs are not detected in the submillimeter bands is due to warmer dust compared with that of SMGs (Kaviani et al. 2003). While testing this requires both robust measurements of the $T_d$ (based on observations that probe the peak of the SED of the galaxies) and a large sample of LBGs, the upper limits that we derived in this study can provide a first insight.

Figure 5 compares dust temperature versus infrared luminosity for the MIPS and IRAC-LBGs as derived from this study. For comparison, we also consider the large compilation of $z \sim 2$ SMGs by Chapman et al. (2005) and the local/intermediate-$z$ samples of ULIRGs presented by Clements et al. (2010) and Yang et al. (2007). In all these studies, the $T_d$ was measured in a manner that is similar to ours, fitting modified blackbody models with fixed $\beta = 1.5$ to the FIR photometric points of each sample, hence the comparison between these studies and our sample is meaningful. We also plot the 3σ envelope of the $L_{IR}-T_d$ relation for local infrared galaxies in Sloan Digital Sky Survey (SDSS; Hwang et al. 2010).

It is evident that for the $L_{IR}$ of the MIPS-LBGs, the bulk of SMGs is considerably colder, while MIPS-LBGs fall in the locus of the local ULIRGs and are within the scatter observed in local galaxies. Based on modified blackbody models, we also compute tracks of constant 850 μm flux density for galaxies at $z = 3$, close to the confusion/detection limit of current submillimeter surveys ($f_{850} = 1$ mJy and $f_{850} = 2$ mJy). MIPS-LBGs lie in between the two tracks, indicating that a typical MIPS-detected LBG emits at 1–2 mJy level at the submillimeter bands, in excellent agreement with the median $f_{850}$ flux density derived from the average SED of the population. This explains the small overlap between the LBGs and SMGs found in previous studies. For a given SFR and optical depth for dust absorption (and hence, for a given bolometric far-infrared luminosity), the warmer dust temperature in LBGs leads to
fainter submillimeter emission compared with that found in typical SMGs. This finding also suggests that star formation in LBGs is spatially compact. On the other hand, recent studies based on minimal excitation (CO (1 - 0) emission that traces the bulk of the metal-rich molecular gas provide evidence of a more extended distribution of star formation in SMGs (e.g., Ivison et al. 2010) that could explain their colder dust compared with that found in typical SMGs, with warmer dust than that of SMGs exist in the high-

We have presented a first glimpse into the far-IR properties of $z \sim 3$ LBGs, demonstrating the power of *Herschel* in the study even of high-$z$ UV-selected galaxies and its ability to address issues that we were unable to resolve in the pre-*Herschel* era. We aim to further extend this study, complementing PACS with SPIRE data that probe the peak of the SED of $z \sim 3$ galaxies and taking advantage of the Super-Deep and Ultra-Deep surveys in GOODS-N and GOODS-S, respectively, as part of the *Herschel*–GOODS program (PI: D. Elbaz).

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Figure 5. $L_{IR}$--$T_d$ relation for MIPS-LBGs and IRAC-LBGs (red and black circles, respectively). We note that these values correspond to 3σ upper and lower $T_d$ limits for IRAC-LBGs and MIPS-LBGs. Included are the results for $0 < z < 0.98$ ULIRGs (blue filled triangles; Clements et al. 2010; Yang et al. 2007). The green shaded region depicts the loci of high-$z$ SMGs by Chapman et al. (2005), while the orange shaded area shows the 2σ envelope of the $L_{IR}$--$T_d$ relation for local IR galaxies in SDSS (excluding AGNs) adopted from Hwang et al. (2010). Black dashed lines represent tracks of constant flux density at 850 μm ($f_{850} = 1 \text{ mJy}$ and $f_{850} = 2 \text{ mJy}$) for galaxies at $z = 3$. Objects at $z = 3$ with higher $f_{850}$ lie on the right of the lines. This plot demonstrates that for a given $L_{IR}$, the bulk of SMGs are considerably colder than MIPS-LBGs which fall in the locus of the local ULIRGs. We also note that for their $T_d$ and $L_{IR}$, MIPS-LBGs fall in between the 1 and 2 mJy constant flux density at 850 μm, indicating that they would be missed by current ground-based submillimeter surveys. Finally, there is a hint that the LBGs at $z \sim 3$ follow the general trend observed in the local universe, with more luminous galaxies having warmer dust.

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