Towards a complete census of high-z ULIRGs with Herschel

Georgios E. Magdis\textsuperscript{1}, D. Elbaz\textsuperscript{1}, H.S. Hwang\textsuperscript{1}, PEP & HerMES team

\textsuperscript{1}CEA Saclay

Abstract. Using Herschel PACS and SPIRE observations as part of the HerMES project, we explore the far-IR properties of a sample of mid-IR selected starburst-dominated ultra-luminous infrared galaxies (ULIRGs) at $z \sim 2$. We derive robust estimates of infrared luminosities ($L_{\text{IR}}$) and dust temperatures ($T_d$) of the population and find that galaxies in our sample range from those that are as cold as high-z sub-millimeter galaxies (SMGs) to those that are as warm as optically faint radio galaxies (OFRGs) and local ULIRGs. We also demonstrate that a significant fraction of our sample would be missed from ground based (sub)mm surveys (850-1200 $\mu$m) showing that the latter introduce a bias towards the detection of colder sources. Similarly, based on PACS data as part of the PEP project, we construct for the first time the full average SED of a sub-sample of infrared luminous Lyman break galaxies at $z \sim 3$, and find them to have higher $T_d$ when compared to that of SMGs with comparable $L_{\text{IR}}$. We conclude that high-z ULIRGs span a wide range of dust temperatures, larger than that seen in local ULIRGs, and that Herschel data provide the means to characterize the bulk of the ULIRG population, free from selection biases introduced by ground based (sub)mm surveys.

1. Introduction

A key parameter to study galaxy evolution is to probe the census of the star formation activity, both in the distant and local universe. To this direction, it has been shown that the contribution of luminous infrared galaxies ($L_{\text{IR}} > 10^{11} L_\odot$) to the star formation density is progressively rising as we look back in the comic time, at least up to $z \sim 2$. Indeed, although they were found to be rare in the local universe and to account only for $\sim 5\%$ of the total infrared energy emitted by galaxies at $z \sim 0$, LIRGs along with the ULIRGs ($L_{\text{IR}} > 10^{12} L_\odot$), dominate the SFR density at $z \sim 1-2$, accounting for the 70\% of the star formation activity at these epochs (e.g. Le Floc’h et al. 2005).

Until recently, the most successful methods for selecting high-z ULIRGs was their direct far-IR detection via ground based (sub)millimeter surveys (e.g. Hughes et al 1996). However, the submillimetre technique introduces a bias towards the selection of ULIRGs with lower dust temperatures while it misses warmer ULIRGs. First observational evidence of a missing population of high-z dusty star-forming galaxies with hotter dust was been given by Chapman et al. (2004) using a selection of radio-detected but sub-mm-faint galaxies (OFRGs) with UV spectra consistent with high-z starbursts. Recent studies (Magnelli et al. 2010 and Chapman et al. 2010) have shown that their is no overlap between the two populations (SMGs and OFRGs) in the $L_{\text{IR}}-T_d$ space, leaving a large gap between them. In other words, it appears that if SMGs are biased towards the colder high-z ULIRGs, then OFRGs trace only the ULIRGs with warmest
2. Far-IR properties of IRAC selected ULIRGs

We select sources with $0.05 < [3.6] - [4.5] < 0.4$, $-0.7 < [3.6] - [8.0] < 0.5$, and $S_{24} > 0.2\text{mJy}$ in Lockman Hole and GOODS-N, and with at least two detections in the either of PACS and SPIRE bands. Our sample consist of 25 ULIRGs with a median $z = 2.01$ and with 18 out of 25 objects lying in narrow redshift range ($1.7 < z < 2.3$) (for details see Magdis et al. 2010a). To derive estimates for the $L_{\text{IR}}$ of the galaxies in our sample, we first convert their SED to rest-frame applying k-corrections and then fit the PACS and SPIRE data with the libraries of Chary & Elbaz (2001) (CE01) and Dale & Helou (2002). Results based on the two methods are in very close agreement indicating a median $L_{\text{IR}} \approx 3 \times 10^{12} \text{L}_\odot$. To derive the dust temperature of galaxies in our sample, we use a single temperature modified black body fitting form. This model was fit to Herschel data with rest-frame > $40\text{\mu m}$, assuming a fixed emissivity index of $\beta=1.5$. Two examples of the rest-frame SEDs along with the best-fit CE01 templates for two ULIRGs in our sample are shown in Figure 1. We find that our sample spans in
wide range of dust temperatures $25 < T_d < 62$ (K), while the luminosities vary by less than an order of magnitude $12.24 < \log(L_{\text{IR}}/L_\odot) < 12.94$. The median values are $T_d = 42.3$ K, and $L_{\text{IR}} = 3 \times 10^{12}$ $L_\odot$.

3. **Herschel reveals a $T_d$ unbiased selection of $z \sim 2$ ULIRGs**

We now compare the far-IR properties of our sample with that of local and high-$z$ ULIRGs selected by different techniques. We consider the large set of $z \sim 2$ SMGs (Chapman et al. 2005 and Kovacs et al. 2006), a sample of $z \sim 2$ OFRGs (Casey et al. 2009, Magnelli et al. 2010) and a compilation of local/intermediate-$z$ ($0 < z < 0.98$) ULIRGs (Clements et al. 2010, Farrah et al. 2003 and Yang et al. 2007). In all these studies, the method to derive $T_d$ estimates is similar to ours, fitting modified blackbody models to the far-IR photometric points and assuming $\beta = 1.5$. This comparison is illustrated in Figure 2 (top).

Our observations confirm the existence of ULIRGs in the high-$z$ universe with dust temperature higher than that of SMGs. Furthermore, it seems that the selection of high-$z$ ULIRGs based on the detection of the 1.6$\mu$m bump does not favour a particular $T_d$, selecting ULIRGs that overlap with the SMGs and OFRGs but also ULIRGs of intermediate $T_d$. Indeed, for the luminosity bin of our sample, SMGs have a median $T_d = 36 \pm 8$ K while OFRGs are considerably warmer with median $T_d = 47 \pm 3$ K (Magnelli et al. 2010) while galaxies in our sample range from those that are as cold as SMGs to objects as warm as OFRGs, with a significant fraction located in the intermediate region between the two samples, bridging the two populations. We also note that a large fraction of the sample falls in the $T_d - L_{\text{IR}}$ relation of the local ULIRGs. Finally, our data indicate that the $T_d$ dispersion of high-$z$ ULIRGs is larger than that of the local ULIRGs as derived based on IRAS/AKARI observations. A similar conclusion is reached by Hwang et al. (2010).

We also estimate the $S_{850}$ flux densities of our sample based on the best fit CE01 model. The predicted $S_{850}$ fluxes of our sample along with the measured sub-mm flux of high-$z$ SMGs are plotted versus the derived $T_d$ of the two populations in Figure 2 (bottom). We also overplot tracks in constant $L_{\text{IR}}$. This plot illustrates that a significant fraction (60%) of the mid-IR selected ULIRGs in our sample have $S_{850}$ flux densities lower than that of the SMGs, lie below the confusion limit at 850$\mu$m (2-3 mJy) and hence would be missed by ground-based (sub)mm surveys. Nevertheless, we also find IRAC-peakers with predicted $S_{850}$ above the detection limit and which therefore should be detected in the sub-mm. Observational data confirm our results, with ~40% of the sample being detected in the submm bands (e.g. Lonsdale et al. 2009). We conclude that our analysis strongly suggests that Herschel data allow us for the first time to characterize the far-IR properties of 50% of the mid-IR selected ULIRGs that would be missed by ground based (sub)mm surveys and reveal that their properties are different from that of SCUBA/IRAM selected galaxies.

4. **$T_d$ of LBGs at $z \sim 3$**

Similar results were reached, when we considered, a sub-sample of 24$\mu$m detected Lyman break galaxies at $z \sim 3$ (MIPS LBGs). Using PACS data as part of the PEP project, we derived a median IR luminosity of $L_{\text{IR}} = 1.6 \times 10^{12}$ $L_\odot$, placing these
Figure 2. top) The $L_{IR} - T_d$ relation for IRAC selected ULIRGs (red circles). Included are results for local/intermediate-$z$ ULIRGs (green filled triangles, Farrah et al. 2003, Clements et al. 2010, Yang et al. 2007), high-$z$ SMGs (blue squares, Chapman et al. 2005, Kovacs et al. 2006) and OFRGs (black squares, Casey et al. 2009). The cyan shaded area denotes the 2σ envelope of the $L_{IR} - T_d$ relation of high-$z$ SMGs. For a given $L_{IR}$, our sample span in a wide range of dust temperatures, bridging the “cold” high-$z$ SMGs to the “warmer” local/intermediate-$z$ ULIRGs and ∼2 OFRGs. bottom) $T_d$ versus the estimated $S_{850}$ flux densities of galaxies in our sample (red circles). We also include $T_d$ measurements and observed $S_{850}$ flux densities of high-$z$ SMGs by Chapman et al. (2005) (blue squares). Solid lines represent tracks in constant $L_{IR}$ while the vertical dotted line indicates the confusion limit of current ground based submm surveys. It is evident that a significant fraction of our sample lies below the detection limit and would be missed the SCUBA-850μm surveys, if we consider that the detection limit should be above the confusion.
galaxies in the class of ULIRGs (Magdis et al. 2010b,c). Considering the large $L_{\text{IR}}$ and the substantial dust reddening of these LBGs it is somewhat surprising that there are only few examples of direct sub-millimeter 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 sub-mm surveys. Based on the average SED of MIPS-LBGs as constructed by stacking at PACS, Aztec1.1mm and VLA1.4GHz maps (Magdis et al. 2010b), we predict that the flux density of the MIPS-LBGs emitted at 850$\mu$m is $S_{850} = 1.1-1.5$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.

In Figure 3 we compare dust temperature versus infrared luminosity for the MIPS LBGs with that of the $z \sim 2$ SMGs by Chapman et al. (2005). We also plot, the $3\sigma$ envelope of the $L_{\text{IR}} - T_d$ relation for local infrared galaxies in SDSS (Hwang et al. 2010). It is evident that for the $L_{\text{IR}}$ of the MIPS-LBGs, the bulk of SMGs are 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 black body models, we also compute tracks of constant 850$\mu$m flux density for galaxies at $z=3$, close to the confusion/detection limit of current sub-mm surveys ($S_{850} = 1$mJy and $S_{850} = 2$mJy). MIPS-LBGs lie in between the two tracks, indicating that a typical MIPS detected LBG emits at 1-2 mJy level at the sub-mm bands. This explains the small overlap between the LBGs and SMGs found in previous studies.
5. Conclusions

Based on Herschel observation of z~2 and ~3 ULIRGs, as part of the PEP and HerMES projects, we explore the far-IR properties of these samples and find that:

- IRAC selected ULIRGs display a wide range of $T_d$, ranging from those that are as cold as high-z SMGs to objects as warm as OFRGs, while a significant fraction has intermediate $T_d$, bridging the two populations. This indicates that the mid-IR selection of high-z ULIRGs does not introduce a systematic bias in $T_d$.

- A significant fraction of z~2 ULIRGs are missed from (sub)mm surveys, showing that the sub-mm technique introduces a bias towards the detection of colder ULIRG sources. On the other hand, Herschel data provide the means for a complete and unbiased selection of the census of ULIRGs at this redshift.

- The $T_d$ dispersion of high-z ULIRGs is larger than that found in the local universe, indicating a wide range of mechanisms triggering the star formation activity at earlier epochs.

- Infrared luminous LBGs at z~3, have warmer $T_d$ than SMGs galaxies while they fall in the locus of the $L_{IR} - T_d$ relation of the local ULIRGs. This, along with estimates based on the average SED, explains the marginal detection of LBGs in current sub-mm surveys and suggests that these latter studies introduce a bias towards the detection of colder ULIRGs in the high-z universe, while missing high-z ULIRGs with warmer dust.

Acknowledgments. Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA. This study is based on data obtained as part of the HerMES and PEP Herschel projects.

References

Chapman, S. C., et al., 2005, ApJ, 622, 772
Chapman, S. C., et al., 2010, MNRAS, 409, 13
Casey, C. M., et al., 2009, MNRAS, 399, 121
Chary, R., Elbaz, D., 2001, ApJ, 556, 562
Clements, D. L., Dunne, L., Eales, S., 2010, MNRAS, 403, 274
Dale, D. A., Helou, G., 2002, ApJ, 576, 159
Farrah, D., et al., 2003, MNRAS, 343, 585
Fiolet et al., 2009, A&A, 508, 117
Huang, J.-S. et al., 2009, ApJ, 700, 183
Hwang, H.S., et al., 2010, MNRAS, 409, 75
Hughes, D. H. et al., 1998, Nature, 394, 241
Kovacs, A., et al., 2006, ApJ, 650, 592
Le Floc’h, E. et al., 2005, ApJ, 632, 169
Lonsdale, C. J. et al., 2009, ApJ, 692, 422
Magdis G.E. et al., 2010a, MNRAS, 409, 22
Magdis G.E. et al., 2010b, ApJ, 720, 185
Magdis G.E. et al., 2010c, ApJ, 714, 1740
Magnelli, B. et al., 2010, A&A, 518, 28
Yang, M., et al., 2007, ApJ, 660, 1198