Herschel-SPIRE, Far-Infrared Properties of Millimetre-Bright and -Faint Radio Galaxies

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We present the first study of the far-infrared (FIR) properties of high redshift, radio-selected Ultraluminous Infrared Galaxies (ULIRGs) using deep observations obtained with the Spectral and Photometric Imaging Receiver (SPIRE) from the Herschel Multi-tiered Extragalactic Survey (HerMES). These galaxies span a large range of 850 µm fluxes from submillimetre-luminous ~10 mJy sources (SCUBA galaxies) to ~1.5 mJy from stacked SCUBA non-detections, thus likely representing a complete distribution of ULIRG spectral energy distributions (SEDs). From Keck spectroscopic surveys in the Lockman-North field we identified a sample of 31 submillimetre galaxies (SMGs) and 37 submillimetre-faint, optically-faint radio galaxies (OFRGs), all with radio-inferred IR luminosities > 10^{12} L_{\odot}. These galaxies were cross-identified with SPIRE 250, 350 and 500 µm catalogs based on fluxes extracted at 24 µm positions in the SWIRE survey, yielding a sample of more than half of the galaxies well detected in at least two of the SPIRE bands. By fitting greybody dust models to the SPIRE photometry together with SCUBA 850 µm measurements (for OFRGs, only 850 µm upper limits), we infer dust temperatures and far-infrared luminosities. The OFRGs detected by SPIRE have median (T_dust) = 41 ± 5 K and the SMGs have (T_dust) = 34 ± 5 K, both in reasonable agreement with previous (pre-Herschel) estimates, reaffirming that the local FIR/radio correlation holds (at least for this subset of high-z ULIRGs) at high redshift (we measure (q_{IR}) = 2.43 ± 0.21 using S_R derived from greybody fit coupled with a powerlaw extrapolation to the 24 µm). Our observations firstly confirm that a substantial fraction of OFRGs exhibit large infrared luminosities corresponding to SFRs of ~ 400 M_{\odot}/yr. The SPIRE observations secondly confirm the higher dust temperatures for these OFRGs than similarly selected SMGs, consistent with early predictions of the submm-faint radio populations. Our observations also clearly confirm the large infrared luminosities of most SMGs selected with S_{850µm} > 5 mJy and radio and strong 24 µm detections, corresponding to SFRs of ~ 700 M_{\odot}/yr.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: infrared – galaxies: starbursts

1 INTRODUCTION

Submillimetre Galaxies (SMGs – Smail, Ivison & Blain 1997) contribute significantly to the rapid build-up of stellar mass in the Universe at z ~ 2. SMGs have a typical redshift of z ~ 2.2 (Chapman et al. 2005; Wardlow et al. 2010), are massive systems (M_{\star} ~ 10^{10}-11 M_{\odot}, Swinbank et al. 2004; Greve et al. 2005; Tacconi et al. 2006) and are diverse in the extent and dynamics of their molecular gas reservoirs (e.g., Tacconi et al. 2008; Bothwell et al. 2010; Ivison et al. 2010a, 2010b). Interferometric observations of SMGs’ CO molecular gas suggest that the most luminous SMGs S_{(500 µm)} > 5 mJy are merging systems (Engel et al. 2010) with high star formation efficiencies compared to typical galaxies of similar mass (Daddi et al. 2008). However, their selection at 850 µm is inherently biased towards colder-dust ULIRGs, particularly at z > 1 (Eales et al. 2006, Blain et al. 2004). In particular, since submm observations probe the blackbody emission of dust in the Rayleigh-Jeans regime, they are anti-correlated with dust temperature (S_{850} \propto T_{\text{dust}}^{-4.5}) for a given infrared luminosity, and galaxies with warmer dust can fall below the detection limit of current submm instruments. Recent work (e.g. Chapman et al. 2004, Casey et al. 2009) has demonstrated that 850 µm-faint, high-redshift ULIRGs exist and may contribute significantly to the cosmic star formation rate density at its peak. These Optically Faint-Radio Galaxies (OFRGs) are defined as radio sources having inferred ULIRG luminosities, with starburst (SB) or hybrid SB-AGN spectral features in the UV, and having 2.5-σ limits on their submm fluxes which are consistent with them being fainter than 5 mJy at 850 µm. They have a comoving volume density (i.e., \sim 10^{-5} Mpc^{-3} at 1 < z < 3, Chapman et al. 2001, 2004), stellar masses and radio sizes comparable to SMGs, and some have a dust temperature of \sim 52 K (Casey et al. 2009, 2010a, 2010b). Studies of other infrared-luminous galaxy populations both pre-Herschel (see Younger et al. 2009, Bussmann et al. 2009) and post-Herschel (see Oliver et al. 2010, Magdis et al. 2010, Roseboom et al. 2010, Chianale et al. 2010) present even more evidence for diverse populations of luminous, dusty starbursts at z > 1.

However, sparse infrared data, particularly in the 50-500 µm wavelength range have limited the interpretation of the SMGs and OFRGs. Many of their fundamental properties still rely on indirect measurements. Direct determinations of SMG and OFRG dust temperatures are limited and have only been done using either a single rest-farIR point (SHARC-II/CSO observed 350 µm – Kovacs et al. 2006, 2010; Coppin et al. 2008) or with the most luminous examples of the population using the highly confused BLAST beam.
Herschel Galaxies at $z > 1$

Observations of the rest-frame far-infrared emission of high-redshift galaxies with Herschel (Pilbratt et al. 2010) provide for the first time direct measurements of typical SMGs and OFRGs total infrared luminosities and dust temperatures, which are still highly debated (e.g., Swinbank et al. 2008; Dave et al. 2008). Importantly, they allow for tests of earlier measurements based on extrapolation from wavelengths either shortward or longerward of the farIR peak. Theoretical simulations of galaxy evolution continue to have difficulties in accounting for the inferred luminosities/star formation rates and number counts (Baugh et al. 2005; Dave et al. 2009; Narayanan et al. 2009). Open questions remain as to whether these luminosities have been overestimated or whether for instance the IMF is significantly more top heavy than in the local Universe (Baugh et al. 2005). In this paper, we assess the Herschel-SPIRE properties of these two ULIRG populations selected using both submillimetre (submm) and radio wavelengths. Calculations assume a flat, $\Lambda$CDM cosmology with $\Omega_\Lambda = 0.7$ and $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 SAMPLE & OBSERVATIONS

The HerMES Science Demonstration Phase (SDP) observations are detailed in Table 1 of Oliver et al. (2010). We use deep Spectral and Photometric Imaging Receiver (SPIRE) (Griffin et al. 2010) 250, 350, 500$\mu$m observations of SMGs and OFRGs lying in the Lockman-East (10h 51m, +57) region (a subset of the larger Lockman-SWIRE field observations) obtained as part of this guaranteed time key program in a key survey field having exquisite multi-wavelength ancillary data. The radio/submm sources lie within a sub-field covered by a deep VLA 1.4GHz radio pointing, within a region of 15' × 15' (Ibar et al. 2009). Flux densities are measured using a PSF fitting technique based on cross-identified (XID) prior sources positions detected at 24$\mu$m (Roseboom et al. 2010), which accounts for blending of SPIRE source fluxes by simultaneous fitting to multiple sources. All sources in our fields are essentially point sources at the resolution of Herschel. The association between the Spitzer-IRAC & MIPS and SPIRE sources is thus facilitated by the use of these priors. The quality of the SPIRE 250, 350, 500$\mu$m catalogs has been estimated using Monte Carlo simulations (photometry error, completeness and contamination as a function of the flux density). In the Lockman-East field our observations have average 1$\sigma$ XID source extraction errors of 3.6 mJy, 4.2mJy and 4.8mJy at 250, 350, 500$\mu$m respectively, and the confusion noise is quoted as 5.8, 6.3 and 6.8mJy/beam rms respectively by Nguyen et al. (2010), which we apply in quadrature to the flux errors.

Some SMGs and OFRGs have previously been studied spectroscopically in Lockman-east in several works (respectively, Chapman et al. 2003a, 2005; Ivison et al. 2005 and Chapman et al. 2004; Casey et al. 2009,2010). The parent sample for this study consists of a sample of 376 radio sources with spectroscopic followup in the Lockman-east field. For this initial foray into the SPIRE properties of luminous, high-z radio sources, we impose a $> 5\sigma$ 24$\mu$m detection threshold (from the SWIRE catalogue – Lonsdale et al. 2004) in order to extract the SPIRE fluxes at that position. This removes some of the confusion issues arising

2 Although for the hotter and lower redshift examples in our sample, PACS observations on the Wien side of the spectrum are required to truly constrain the dust temperature

3 hermes.sussex.ac.uk, Oliver et al. 2010 (in prep.)
in the full radio source sample, although it brings some bias to the study. We adopt a catalogue based on a 24μm prior, as opposed to a radio prior, as we have uniform 24μm coverage across these areas and a clear understanding of the effect of this input list on the data. Future contributions will include a broader radio prior catalog to further explore these populations. This catalog consists of 140 sources. We further restrict this sample to those with radio luminosities $> 4.5 \times 10^{30}$ ergs/s/Hz, corresponding to an equivalent ULIRG far-IR luminosity ($> 10^{12} L_\odot$) assuming the radio-farIR correlation (e.g. Condon et al. 1991), resulting in a sample of 68 sources.

The final sample consists of 31 securely identified SMGs and 37 OFRGs with IR luminosities $> 10^{12} L_\odot$, and which are cross-matched with our SPIRE 250, 350, 500μm multi-wavelength catalogs based on sources extraction using prior detections at 24μm. 19 of the SMGs and 21 of the OFRGs in our sample are detected in at least two of the SPIRE bandpasses, and form the sample we focus on in this work. The SMGs have an average (deboosted using the Coppin et al. 2006 counts and method) $S_{850\mu m}=6$mJy while the OFRGs have average $S_{850\mu m}=1.5$mJy (which we have not attempted to deboost here), together likely representing a complete distribution of ULIRG SEDs. In figure 1 we plot the average SEDs of SMGs and OFRGs which is constructed by redshifting each template fit to the rest-frame, and interpolating observed data points at the average redshift of the sample. The dispersion in the average SED is comparable to the individual flux errors combined with confusion noise. Figure 1 also compares the Dale & Helou SED templates (Dale et al. 2001, $L_{\text{IR}}$) assuming the radio-optically thin approximation, with a single dust temperature model; with a color-correction term (Dale et al. 2001, $L_{\text{IR}}$). While the effect is still moderate such that the optically thin model yields high $\chi^2$ values. All these galaxies appear either to be the less luminous examples, exhibit far-infrared colours possibly suggestive of hotter systems, or may simply lie in confused regions. However, given the extreme dust masses ($\sim 10^9 M_\odot$) of SMGs, one should expect optical depths to matter, especially in the shorter wavelength SPIRE bands. Assuming typical emission scales of $\sim 2$ kpc, we expect optical depths of 1–2 in the 250μm and 350μm bands for a $z \sim 2$ SMG (see Kovacs et al. 2010). While the effect is still moderate such that the optically thin approximation is crudely correct, the high $\chi^2$ found for some of the galaxies may be an indication of the shortcoming of the single-T, optically thin model.

Our results appear to be relatively insensitive to $\beta$ and to the single dust component model; with $\beta = 2$, the differences in $T_\text{d}$ are $\Delta T_\text{d} \pm 3$ K. In addition, the multiple dust components model of Dale & Helou (2002) yields rest-frame infrared colors ($S_{350\mu m}/S_{1000\mu m}$), or equivalently $T_\text{d}$, which are in reasonable agreement with those inferred from our greybody analysis. In figure 1, we also overplot a composite SMG spectrum, from Pope et al. (2008), normalized to 24μm flux density.

The $T_\text{d}$-$L_{\text{IR}}$ plane forms an important diagnostic for assessing the properties of luminous IR galaxies and their spectral shapes. In Figure 2, the locations of our SMGs and OFRGs on the $T_\text{d}$-$L_{\text{IR}}$ plane are shown. These estimates are amongst the first direct observational measurements of the dust temperatures and the infrared luminosities of OFRGs. Previous studies with SHARC-II and BLAST have

\begin{equation}
S_{\nu} \propto \frac{\nu^{\beta}}{\exp(h\nu/kT_\text{dust}) - 1}
\end{equation}

where $S_{\nu}$, the flux density, is a function of rest frequency $\nu$, the emissivity $\beta$, dust temperature $T_\text{d}$, and FIR luminosity $L_{\text{IR}}$ (which governs the normalization of the function). Their total infrared luminosities ($L_{\text{IR}}[8\text{–}1000\mu m]$) are inferred from these best fit using the far-infrared luminosity denition ($L_{\text{FIR}}[40\text{–}120\mu m]$) given by Helou et al. (1988) and a color-correction term (Dale et al. 2001, $L_{\text{IR}} = 1.91 \times L_{\text{FIR}}$). The model fixes emissivity to $\beta = 1.5$. The model has $T_\text{d}$ and $L_{\text{IR}}$ as free parameters. While the luminosities here are clearly an approximation to the true $L_{\text{IR}}$, we leave a more detailed estimation to the availability of shorter wavelength Herschel data. We choose to make this model rigid since the flux errors are known to be correlated which reduces the effective number of degrees of freedom.

This single dust temperature characterisation provides a good description of the SMGs and OFRGs far-infrared SED, however for 7 SMGs and 9 OFRGs, this single dust temperature model yields high $\chi^2$ values. All these galaxies appear either to be the less luminous examples, exhibit far-infrared colours possibly suggestive of hotter systems, or may simply lie in confused regions. However, given the extreme dust masses ($\sim 10^9 M_\odot$) of SMGs, one should expect optical depths to matter, especially in the shorter wavelength SPIRE bands. Assuming typical emission scales of $\sim 2$ kpc, we expect optical depths of 1–2 in the 250μm and 350μm bands for a $z \sim 2$ SMG (see Kovacs et al. 2010). While the effect is still moderate such that the optically thin approximation is crudely correct, the high $\chi^2$ found for some of the galaxies may be an indication of the shortcoming of the single-T, optically thin model.

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attempted similar analyses mainly on SMGs with caveats presented in the Introduction (Kovacs et al. 2006, 2010, Coppin et al. 2008; Ivison et al. 2010c, Dunlop et al. 2010, Chapin et al. 2010, Casey et al. 2010, Amblard et al. 2010). Our observations suggest that high redshift ULIRGs show a wide range of dust temperatures. At intermediate infrared luminosities of ULIRGs (L_{IR} \sim 3 - 5 \times 10^{12} \, L_{\odot})

The SMG composite template (Pope et al. 2008) used in Fig. 1 is derived based on mid-IR to FIR data of SMGs. Since our S_{850\mu m} estimates are based on the greybody fits, we extrapolate from the peak to the 24\mu m point with an appropriate power-law, yielding \langle q_{IR} \rangle = 2.43 \pm 0.2, thereby suggesting a reliable estimate of the infrared luminosity of z \sim 2 ULIRGs can be obtained from their radio luminosity using a similar q to that inferred locally, as inferred in Kovacs et al. (2006,2010).

The SMG composite template (Pope et al. 2008) used in Fig. 1 is derived based on mid-IR to FIR data of SMGs to date. While it reasonably fits the SPIRE FIR data of the SMG sample, in some cases, it under/overestimates the FIR luminosities by \pm 0.5 dex, and unsurprisingly is much worse at describing the OFRG sample. This illustrates how a 24\mu m-normalized SED fitting procedure, which is common in the literature (Desai et al. 2009) places poor constraints on the breadth of FIR properties of ULIRG samples, especially in the absence of direct FIR measurements. Similarly, the use of the 24\mu m emission and of the Chary & Elbaz SED library yields an inaccurate estimate of the infrared luminosity characterized by a large scatter (\sim 0.5 dex) and a systematic overestimation (\sim \times 2 times) in the luminosities

\[ q_{IR} = \log\left(\frac{S_{IR}}{3.75 \times 10^{22} W \, m^{-2}}\right) - \log\left(\frac{S_{1.4 \, GHz}}{W \, m^{-2} \, Hz^{-1}}\right) \]

Figure 3. Submm flux densities as function of the redshift and Far-Infrared luminosity, revealing both the redshift distribution of our sample and the range in 850\mu m fluxes probed for two samples which have similar average radio fluxes. Symbols are same as in Fig. 2 except the OFRGs for which we have only upper limits (flux+2\sigma). Solid and dashed lines show the linear fit to the S_{850\mu m} - \langle L_{IR} \rangle relation for SMGs and the 1\sigma envelope.

4 DISCUSSION

Comparing to previous studies of SMG dust temperatures, Chapman et al. (2005) found T_{d} = 36 \pm 7 \, K by using the FIR/radio correlation (e.g., Condon et al. 1991). As mentioned earlier, these measurements relied on indirect indicators of T_{d}. In order to more directly compare our SPIRE results with previous studies, we applied the method of Chapman et al. (2005) to our SMG sample, using only the radio and 850\mu m data and fitting Dale & Helou (2002) dust SED templates. T_{d} is then derived by applying a mapping from their S_{850\mu m}/S_{100\mu m}. Using the full SED information for these SPIRE sources, we find that T_{d}, measured from S_{850\mu m} and L_{1.4 \, GHz} alone, overestimates the dust temperature by 2 \pm 2 \, K for SMGs, and on average overestimates the dust temperature of OFRGs by 7 \pm 4 \, K. This is remarkable agreement, given the scatter in the IR-radio relation and poorly defined 850\mu m fluxes for individual OFRGs. Kovacs et al. (2006) observed 21 SMGs at 350\mu m and measured FIR luminosities independent of radio luminosity using FIR data ranging from observed 350\mu m to 1200\mu m. They found that the local FIR/radio correlation overestimates FIR luminosity by factors of \sim 0.2-0.4 dex for SMGs, which agrees with our SPIRE analysis.

To demonstrate these discrepancies more clearly, we estimate the bolometric q_{IR}, the ratio of IR integrated flux to radio flux, as described in Ivison et al. (2010d):

\[ q_{IR} = \log\left(\frac{S_{IR}}{3.75 \times 10^{22} W \, m^{-2}}\right) - \log\left(\frac{S_{1.4 \, GHz}}{W \, m^{-2} \, Hz^{-1}}\right) \]
of ULIRGs. For radio-ULIRGs under investigation here, luminosity extrapolations based on the radio emission are considerably more reliable than those based on the mid-infrared emission (e.g., Elbaz et al. 2010, although they have shown that 24µm is a good representation of LIR for lower redshift galaxies).

It is of interest to estimate the expected infrared luminosities of our SPIRE-undetected SMGs and OFRGs, although in the latter case there is some likelihood that an AGN is boosting the radio luminosity. The SPIRE nondetections of SMGs are generally found to be consistent with the properties inferred from the detections. We use (µµIR)=2.43 and apply the Dale & Helou SED templates normalized to these infrared luminosities. For the SMGs we find that for 5 out of 11 undetected SMGs, SPIRE flux densities inferred using these fits lie below the detection threshold. Of the 6 sources with predictions for SPIRE fluxes above the detection threshold, 3 have evidence in the UV spectra for AGN contributions. For the OFRGs the lack of 850µm detection and SPIRE detections makes it likely that an AGN is generating the radio luminosity.

The main concern with this study is just how representative the sample of ULIRGs is to the wider SMG and OFRG populations given the use of a 24µm prior. The 24µm detection could favour those galaxies that are either warmer, or have larger fractions of warm (T>35K) gas than average, biasing both the luminosities and temperatures. Apart from misrepresenting the class of objects as a whole, the different temperature distributions also question the usability of local templates (which presumably have a more average temperature distribution). Also, because the 24µm band falls into a range of the rest-frame spectrum where there are a lot of aromatic features, it is even more complicated to assess what subclasses are selected at what redshift. While our study has some clear advantages compared to prior FIR studies of SMGs and OFRGs, the additional bias is a disadvantage, motivating a more thorough investigation of the SPIRE properties of more complete samples.

Our observations firstly confirm that a substantial fraction of OFRGs (~50% of the 24µm XID SPIRE sample) exhibit large infrared luminosities corresponding to SFRs of 300 M⊙/yr (SFR [M⊙/yr] = 0.5×10^{-9} LIR [L⊙], assuming a Chabrier IMF). The complicated selection of our sample in this study, including the required 24µm XID prior for SPIRE flux extraction, means that a precise volume density for these IR-luminous OFRGs is not trivial to estimate. As a lower limit, given the OFRGs without 24µm SFR > 0.5 M⊙/yr (SFR [M⊙/yr] = 0.5×10^{-9} LIR [L⊙], assuming a Chabrier IMF) and the complicated selection of our sample in this study, including the required 24µm XID prior for SPIRE flux extraction, means that a precise volume density for these IR-luminous OFRGs is not trivial to estimate. As a lower limit, given the OFRGs without 24µm XID prior which have yet to be studied with Herschel, the IR-luminous OFRGs are about 1/4 as numerous as equivalent luminosity SMGs at z ~ 2, or > 7 × 10^{-6} Mpc^{-3} for LIR = 2.6×10^{12} L⊙. The SPIRE observations secondly confirm the higher dust temperatures for these OFRGs than similarly selected SMGs with SPIRE observations, consistent with our early predictions of the submm-faint radio populations. Understanding the different dust temperatures and the connections to SMGs is possible if we take the luminosities of SMGs and OFRGs as dominated by star-formation, even if an AGN contribution cannot be ruled out. Since L ∝ M_{d} T^{-0.5}, warmer dust implies less dust. As such, given the similar SMG and OFRG luminosities but their different typical temperatures, a possible conclusion is simply that OFRGs have about a third of the dust content relative to stellar mass. This would naturally suggest that OFRGs are simply a different phase of the starburst than the cooler SMGs. Either OFRGs are an earlier phase, before the full-scale build-up of dust mass, or a later phase, when much of the dust is blown out by superwinds or consumed by a central black hole.

Our observations also clearly confirm the remarkably large infrared luminosities of most SMGs (S_{850µm} > 5 mJy) which correspond to SFRs of 710 M⊙/yr. The remaining 12 SMGs in our Lockman-East catalog which are not found in the XID SPIRE catalog do not distinguish themselves in terms of 850µm or 24µm fluxes. Although their radio-850µm inferred T_d is cooler on average than those presented here, it is likely source confusion in the SPIRE maps which limits their study. More detailed evolutionary understanding of high-z ULIRGs will be facilitated by future studies of deep Herschel observations and including the shorter wavelength bands.

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