Herschel: the first science highlights

Far-infrared properties of submillimeter and optically faint radio galaxies

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ABSTRACT

We use deep observations obtained with the Photodetector Array Camera and Spectrometer (PACS) onboard the Herschel Space Observatory to study the far-infrared (FIR) properties of submillimeter and optically faint radio galaxies (SMGs and OFRGs). From literature we compiled a sample of 35 securely identified SMGs and nine OFRGs located in the GOODS-N and the A2218 fields. This sample is cross-matched with our PACS 100 μm and 160 μm multi-wavelength catalogs based on sources-extraction using prior detections at 24 μm. About half of the galaxies in our sample are detected in at least the PACS 160 μm bandpass. The dust temperatures and the infrared luminosities of our galaxies are derived by fitting their PACS and SCUBA 850 μm (only the upper limits for the OFRGs) flux densities with a single modified (β = 1.5) black body function. The median dust temperature of our SMG sample is $T_{\text{dust}} = 36 \pm 8$ K while for our OFRG sample it is $T_{\text{dust}} = 47 \pm 3$ K. For both samples, median dust temperatures derived from Herschel data agree well with previous estimates. In particular, Chapman et al. (2005, ApJ, 622, 772) found a dust temperature of $T_{\text{dust}} = 36 \pm 7$ K for a large sample of SMGs assuming the validity of the FIR/radio correlation (i.e., $q = \log_{10}(L_{\text{IR}}/L_{\text{FIR}})} + \log_{10}(\text{LHz^{-1}}) / 103.5$. The agreement between our studies confirms that the local FIR/radio correlation effectively holds at high redshift even though we find $(q) = 2.17 \pm 0.19$, a slightly lower value than that observed in local systems. The median infrared luminosities of SMGs and OFRGs are 4.6$\times 10^{42}$ $L_{\odot}$ and 2.6$\times 10^{42}$ $L_{\odot}$, respectively. We note that for both samples the infrared luminosity estimates from the radio part of the spectral energy distribution (SED) are accurate, while estimates from the mid-IR are considerably ($\sim 3 x$) more uncertain. Our observations confirm the remarkably high luminosities of SMGs and thus imply median star-formation rates of 960 $M_{\odot}$ yr$^{-1}$ for SMGs with $S(850 \mu m) > 5$ mJy and 460 $M_{\odot}$ yr$^{-1}$ for SMGs with $S(850 \mu m) > 2$ mJy, assuming a Chabrier IMF and no dominant AGN contribution to the far-infrared luminosity.

Key words. infrared: galaxies – submillimeter: galaxies – galaxies: evolution – galaxies: starburst

1. Introduction

Herschel observations probe the rest-frame far-infrared emission of high-redshift galaxies. Thus, they provide for the first time robust estimates of the infrared luminosities of these high-redshift galaxies and test previous measurements that were based on extrapolation from shorter or longer wavelengths. We here focus on two populations of high-redshift star-forming galaxies selected at submillimeter (submm) and radio wavelengths.

Since their discovery in the late 1990s, submillimeter galaxies (SMGs) have become the selection of choice for the most luminous tail of the high-redshift star-forming galaxy population. It has been found that SMGs have a typical redshift of $z \sim 2$ (Chapman et al. 2005; Pope et al. 2006), are massive systems ($M_{*} \sim 10^{10}-10^{11} M_{\odot}$, Swinbank et al. 2004; Tacconi et al. 2006) and are compact (e.g., Tacconi et al. 2008).
Interferometric observations of their CO molecular gas suggest that the most luminous SMGs ($S_{850\mu m} > 5 mJy$) are merging systems (Tacconi et al. 2006, 2008) with high star-formation efficiencies compared to typical galaxies of a similar mass (Daddi et al. 2008). Therefore, these SMGs are thought to exhibit very intense ($SFR \sim 1000 M_\odot yr^{-1}$) short-lived star-formation bursts triggered by mergers and to be the high-redshift progenitors of local massive early-type galaxies (Daddi et al. 2007a,b; Tacconi et al. 2008; Cimatti et al. 2008).

Although SMGs provide a powerful tool to constrain the formation and the evolution of high-redshift dusty star-forming galaxies, their selection is subject to strong biases. In particular, because submm observations probe the blackbody emission of dust in the Rayleigh-Jeans regime, they are strongly biased towards dusty star-forming galaxies with hot dust. Those submm point sources (i.e. $S_{850\mu m} > 5 mJy$) are likely to be lensed sources detected in A2218. The PACS sample is slightly biased towards lower redshift sources because of the positive contamination as a function of the flux density. In the GOODS-N field our observations reach a 3$\sigma$ limit of $\sim 3 mJy$ and $\sim 5 mJy$ at 100 $\mu m$ and 160 $\mu m$ respectively, while in the A2218 field they reach a 3$\sigma$ limit of $\sim 2.5 mJy$ and $\sim 5 mJy$ at 100 $\mu m$ and 160 $\mu m$ respectively.

A complete description of PEP data reduction and sources extraction is given in Appendix A of Berta et al. (2010).

3. Galaxy sample

To obtain a robust measurement of the dust temperature and infrared luminosity of a given galaxy one needs to have an accurate estimate of its redshift. Consequently, we decided to restrict our study to a sample of SMGs and OFRGs with accurate redshift estimates derived from secured radio/mid-infrared identifications (PACS identifications of SMGs are presented in Dannerbauer et al. in prep). In the GOODS-N field, our SMG sample is based on multi-wavelength identifications of SCUBA and AzTEC sources made by Pope et al. (2006) and Chapin et al. (2009), respectively. SMGs with tentative redshifts determined from their IRAC or mid/far-infrared/radio colors were excluded from our sample. Sources with multiple optical counterparts (GN04, GN07, GN19 and GN39) were treated as a single system (i.e. we will use the sum of the radio and mid-infrared flux from the two components when determining their far-infrared properties) because they are all thought to be interacting galaxies (Pope et al. 2006). All these different criteria yield an SMG sample containing 29 sources in the GOODS-N field. In the A2218 field, our SMG sample is assembled from the literature (Kneib et al. 2004; Knudsen et al. 2006, 2008) and contains six lensed sources. Because these galaxies are magnified, their mid-to-far infrared fluxes were de-magnified prior to further analysis using magnification factors from the above references. Among these six lensed sources, three correspond to the same lensed galaxy (SMMJ1635+6612; Kneib et al. 2004). Finally, our OFRG sample is taken from Casey et al. (2009a,b) and contains nine sources, all situated in the GOODS-N field. We note that all but three sources of our entire sample (i.e. SMGs and OFRGs) have spectroscopic redshifts.

The SMG and OFRG samples were cross-matched with our PACS multi-wavelength catalogs using a matching radius of 3″. We detected 19 out of 35 SMGs in at least the PACS 160 $\mu m$ bandpass (17 out of 33 if not multi-counting the 3-component lensed source detected in A2218). The PACS sample is slightly biased towards lower redshift sources because of the positive $K$-correction: while the median redshift of our parent SMG sample is $z = 2$, the median redshift of our PACS detected SMG sample is $z = 1.7$. Five out of nine OFRGs have PACS 100 $\mu m$ and 160 $\mu m$ detections. This sample is also slightly biased toward lower redshift ($z = 1.5$) because the OFRG situated at the highest redshift is undetected in our PACS images.

We note that our SMG sample contains sources with 2 mJy < $S_{850\mu m} < 5 mJy$, while the most luminous tail of the SMG population, mostly associated with major mergers, is defined using $S_{850\mu m} > 5 mJy$. Below, we will draw our conclusions distinguishing these two populations of SMGs.

\footnote{For GN05, GN07, GN10, GN20 and GN20.2, we used the spectroscopic redshifts revised in Pope et al. (2008) and Daddi et al. (2009a,b).}
In order to infer the dust temperature of our galaxies we fitted their PACS and SCUBA photometry (only the upper limit for the OFRGs) with a modified blackbody function, with a dust emissivity $\beta = 1.5$ (see Fig. 1). Their total infrared luminosities ($L_{\text{IR}}[8-1000\mu m]$) were inferred from these best fits using the far-infrared luminosity definition ($L_{\text{IR}}[40-120\mu m]$) given by Helou et al. (1988) and a color-correction term (Dale et al. 2001, $L_{\text{IR}} = 1.91 \times L_{\text{IR}}$).

We adopted a single dust temperature characterization because studies of IRAS galaxies have demonstrated that this provides an accurate diagnostic of the typical heating condition in their interstellar medium (Desert et al. 1990). While for most of our galaxies this single dust temperature characterization provides a good description of their far-infrared SED, for 6 SMGs, this single dust temperature model yields high $\chi^2$ values (i.e. $\chi^2 > 2.71 + N_{\text{dof}}$). All these galaxies appear either to be the more distant ones or to exhibit far-infrared colors typical of very cold systems. In both cases, their PACS 100 $\mu$m flux densities might be contaminated by a hotter dust component. Therefore we excluded their PACS 100 $\mu$m photometry from the fit and recomputed their dust temperatures. We note that excluding the PACS 100 $\mu$m photometry from the fit of all our galaxies changes their median dust temperature by only $\Delta T_{\text{dust}} \sim 2$ K.

We tested that our results are relatively insensitive to $\beta$ and to our single dust component characterization. Indeed we note that using $\beta = 2$, we found only small differences in the values of $T_{\text{dust}}$ ($\Delta T_{\text{dust}} \sim +3$ K). Moreover, we also note that to fit the PACS and SCUBA photometry with the multiple dust components model of Dale & Helou (2002) yields rest-frame infrared colors ($S_{850\mu m}/S_{100\mu m}$), or equivalently $T_{\text{dust}}$, which excellently agree with those inferred from our blackbody analysis.

### 5. Discussion

Figure 2 depicts the locations of our SMGs and OFRGs on the $T_{\text{dust}} - L_{\text{IR}}$ plane and Fig. 3 shows their locations on the $S_{850\mu m} - L_{\text{IR}}$ plane. As already mentioned, OFRGs are biased towards hot dust temperatures; their median $T_{\text{dust}}$ is of 47 ± 3 K and their median $L_{\text{IR}}$ is 2.6 × 10^{12} $L_{\odot}$. In contrast, SMGs have lower dust temperatures with median $T_{\text{dust}} = 36$ ± 8 K and $L_{\text{IR}} = 4.6 \times 10^{12} L_{\odot}$. We note that lensed-SMGs from A2218 and with $L_{\text{IR}} < 2 \times 10^{12} L_{\odot}$ exhibit intermediate dust properties and are less biased towards cold dust temperatures than the entire SMG sample. This is because these galaxies would have escaped both the SMG and OFRG selection method without magnification. We also note that bright SMGs (i.e. $S_{850\mu m} > 5$ mJy) have higher median infrared luminosities ($L_{\text{IR}} = 9.6 \times 10^{12} L_{\odot}$) and higher median dust temperatures ($T_{\text{dust}} = 38$ K) than the entire
SMG sample because there is a correlation between $S_{850\mu m}$ and $L_{IR}$ (Fig. 3). These estimates are the first direct observational measurements of the dust temperatures and the infrared luminosities of SMGs and OFRGs.

Our observations reveal that high redshift dusty star-forming galaxies exhibit a wide range of dust temperatures. In particular at low infrared luminosities ($L_{IR} < 4 \times 10^{12} L_\odot$) the dust temperature dispersion observed in our sample might suggest a higher $T_{dust} - L_{IR}$ scatter than that observed by Chapman et al. (2003) at $z \sim 0$. Nevertheless, this conclusion is most likely driven by selection effects because a significant fraction of the galaxies with intermediate dust properties were probably missed by our current sample. Indeed, we note that studying a $L_{IR}$-selected sample of galaxies observed with Herschel, Hwang et al. (in prep) find modest changes in the $T_{dust} - L_{IR}$ relation as function of the redshift: at $z > 0.5$, galaxies with $L_{IR} > 5 \times 10^{10} L_\odot$ are slightly colder ($\sim 3$ K) than local ones and the scatter of the $T_{dust} - L_{IR}$ relation slightly increases at high redshift.

Though previous estimates of the dust temperatures of SMGs and OFRGs relied on indirect observations, they agree relatively well with our measurements. In particular Chapman et al. (2005) found a dust temperature of $T_{dust} = 36 \pm 7$ K for a large sample of SMGs assuming the validity of the FIR correlation. In order to establish this agreement on a common sample, we applied the same method as Chapman et al. (2005) to our SMG sample, i.e. we fitted the radio and $850 \mu m$ photometries with dust SED templates from Dale & Helou (2002) and then translated them into $T_{dust}$ using their $R(60, 100)$ to $T_{dust}$ map. With this method we found higher $T_{dust}$ (by $\sim 4$ K) and $L_{IR}$ ($\sim \times 1.5$ times) than what we obtained using our blackbody analysis. These discrepancies arise because the Dale & Helou SED templates assume a FIR/radio correlation. In order to establish this agreement on a common sample, we applied the same method as Chapman et al. (2005) to our SMG sample, i.e. we fitted the radio and $850 \mu m$ photometries with dust SED templates from Dale & Helou (2002) and then translated them into $T_{dust}$ using their $R(60, 100)$ to $T_{dust}$ map. With this method we found higher $T_{dust}$ (by $\sim 4$ K) and $L_{IR}$ ($\sim \times 1.5$ times) than what we obtained using our blackbody analysis. These discrepancies arise because the Dale & Helou SED templates assume a FIR/radio correlation. In order to establish this agreement on a common sample, we applied the same method as Chapman et al. (2005) to our SMG sample, i.e. we fitted the radio and $850 \mu m$ photometries with dust SED templates from Dale & Helou (2002) and then translated them into $T_{dust}$ using their $R(60, 100)$ to $T_{dust}$ map. With this method we found higher $T_{dust}$ (by $\sim 4$ K) and $L_{IR}$ ($\sim \times 1.5$ times) than what we obtained using our blackbody analysis. These discrepancies arise because the Dale & Helou SED templates assume a FIR/radio correlation. In order to establish this agreement on a common sample, we applied the same method as Chapman et al. (2005) to our SMG sample, i.e. we fitted the radio and $850 \mu m$ photometries with dust SED templates from Dale & Helou (2002) and then translated them into $T_{dust}$ using their $R(60, 100)$ to $T_{dust}$ map. With this method we found higher $T_{dust}$ (by $\sim 4$ K) and $L_{IR}$ ($\sim \times 1.5$ times) than what we obtained using our blackbody analysis. These discrepancies arise because the Dale & Helou SED templates assume a FIR/radio correlation. In order to establish this agreement on a common sample, we applied the same method as Chapman et al. (2005) to our SMG sample, i.e. we fitted the radio and $850 \mu m$ photometries with dust SED templates from Dale & Helou (2002) and then translated them into $T_{dust}$ using their $R(60, 100)$ to $T_{dust}$ map. With this method we found higher $T_{dust}$ (by $\sim 4$ K) and $L_{IR}$ ($\sim \times 1.5$ times) than what we obtained using our blackbody analysis. These discrepancies arise because the Dale & Helou SED templates assume a FIR/radio correlation.

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