UNVEILING FAR-INFRARED COUNTERPARTS OF BRIGHT SUBMILLIMETER GALAXIES USING PACS IMAGING

H. Dannerbauer1, E. Daddi1, G. E. Morrison2,3, B. Altieri4, P. Andreani5,6, H. Aussel7, S. Berta7, A. Bongiovanni8,9, A. Cava8,9, J. Cepa8,9, A. Cimatti10, H. Dominguez11, D. Elbaz1, N. Förster Schreiber7, R. Genzel7, C. Gruppioni11, B. Horée1, H. S. Hwang1, E. Le Floc’h1, J. Le Pennec1, D. Lutz7, G. Magdis1, B. Magnelli7, R. Maiolino12, R. Nordon7, A. M. Pérez García8,9, A. Poglitsch7, P. Popesso7, F. Pozzi10, L. Riguccini1, G. Rodighiero13, A. Saintonge7, P. Santini12, M. Sanchez-Portal5, L. Shao7, E. Sturm7, L. Tacconi7, and I. Valtchanov4

1 Laboratoire AIM, CEA/DSM–CNRS–Université Paris Diderot, DAPNIA/Service d’Astrophysique, CEA Saclay, Orme des Merisiers, F-91191 Gif-sur-Yvette Cedex, France; helmut.dannerbauer@cea.fr
2 Institute for Astronomy, University of Hawaii, Manoa, HI 96822, USA
3 Canada-France-Hawaii Telescope Corp., Kamuela, HI 96743, USA
4 Herschel Science Centre, European Space Astronomy Centre, ESA, Villanueva de la Cañada, 28691 Madrid, Spain
5 ESO, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany
6 INAF-Osservatorio Astronomico di Trieste, via Tiepolo 11, 34143 Trieste, Italy
7 Max-Planck-Institut für Externestrerische Physik (MPIE), Postfach 1312, 85741 Garching, Germany
8 Instituto de Astrofísica de Canarias, 38205 La Laguna, Spain
9 Departamento de Astrofísica, Universidad de La Laguna, Spain
10 Dipartimento di Astronomia, Università di Bologna, Via Ranzani 1, 40127 Bologna, Italy
11 INAF-Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy
12 INAF-Osservatorio Astronomico di Roma, via di Frascati 33, 00040 Monte Porzio Catone, Italy
13 Dipartimento di Astronomia, Università di Padova, Vicolo dell’Osservatorio 3, 35122 Padova, Italy

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ABSTRACT

We present a search for Herschel-PACS counterparts of dust-obscured, high-redshift objects previously selected at submillimeter and millimeter wavelengths in the Great Observatories Origins Deep Survey North field. We detect 22 of 56 submillimeter and millimeter sources have been selected through submillimeter/millimeter imaging with bolometer cameras like SCUBA, LABOCA, AzTEC, and MAMBO (e.g., Hughes et al. 1998; Dannerbauer et al. 2002, 2004; Smail et al. 2002; Coppin et al. 2006; Pope et al. 2006; Bertoldi et al. 2007; Perera et al. 2008; Weiß et al. 2009). The large beam size in the (sub)millimeter (e.g., MAMBO: 11′′, SCUBA: 15′′, and LABOCA: 19′′) hampers the identification of these so-called submillimeter galaxies (SMGs; see, for a review, Blain et al. 2002) based on bolometer data only. The most obvious choice for obtaining the subarcsecond accurate positions of the dust continuum is (sub)millimeter interferometric continuum observations (e.g., Dannerbauer et al. 2002, 2008; Younger et al. 2007). However, the slow mapping speed of (sub)millimeter interferometers does not allow us to study a large number of sources. The most suitable tool for counterpart identification is interferometric observations at radio wavelengths. About 50%–80% of these submillimeter/millimeter sources have been identified, mainly based on radio observations, and the peak of the redshift distribution of the radio-identified SMG population lies at <z> = 2.2 (Chapman et al. 2005). However, the effect of the bias toward the true redshift distribution introduced by the radio selection technique is still under debate, as SMGs even beyond z = 4 have already been detected by the Very Large Array (VLA) at 20 cm (e.g., Daddi et al. 2009a, 2009b; Capak et al. 2008; Schinnerer et al. 2008; Coppin et al. 2009; Knudsen et al. 2010; Morrison et al. 2010). The sample of unidentified SMGs could consist of either spurious sources or sources that lie at extreme redshifts, but no systematic studies on this subsample of SMGs have been conducted so far.

The launch of the Herschel observatory (Pilbratt et al. 2010) promises a different perspective of SMGs than that provided by radio observations only and offers a higher mapping speed than (sub)millimeter interferometric observations. Deep Photodetector Array Camera and Spectrometer (PACS) (Poglitsch et al. 2010) imaging at 100 μm and 160 μm on the Great Observatories Origins Deep Survey North (GOODS-N) will sample the FIR emission of these dust-enshrouded high-z objects and enable us to study in detail their far-infrared spectral energy distribution (SED), redshift distribution, dust temperatures (Magnelli et al. 2010; Elbaz et al. 2010; P. Chianial et al. 2010).
In case that an SMG is detected at submillimeter and millimeter bands, we give preference to the SCUBA detection and include it in our sample. For millimeter-only detected sources, we list, if available, the AzTEC otherwise the MAMBO detection.

In this Letter, we discuss our search for PACS counterparts at 100 \(\mu\)m and 160 \(\mu\)m, explore the diagnostic potential of Hereschel-PACS for the counterpart identification, and compare it with the widely used identification approach using VLA observations. In comparison, the Spitzer-Multiband Imaging Photometer (MIPS) 70 \(\mu\)m and 160 \(\mu\)m imaging of the GOODS-N region performed by Huynh et al. (2007) in the pre-Herschel era detected at relatively high significance only 2 (1) out of 30 SMGs at 70 \(\mu\)m (160 \(\mu\)m), at rather low redshifts (\(z = 0.5\) and \(z = 1.2\)). The FIR observations presented here will enable us to study a significant sample of SMGs in the far-infrared wavelength regime.

2. FAR-INFRARED ASSOCIATION OF SUBMILLIMETER GALAXIES

PACS observations of the GOODS-N region at 100 \(\mu\)m and 160 \(\mu\)m were taken during the Herschel Science Demonstration Phase in autumn 2009 and are part of the Guaranteed Time extragalactic PACS survey “PEP. The PACS Evolutionary Probe” (PI: D. Lutz). The final images achieve 3\(\sigma\) sensitivities of \(\sim 3.0\) mJy and \(\sim 5.7\) mJy at 100 \(\mu\)m and 160 \(\mu\)m, respectively. Berta et al. (2010) describe in their Appendix the Herschel-PACS observations, data reduction, and the blind extraction of PACS sources with signal-to-noise ratio (S/N) \(\geq 3\). D. Lutz et al. (2010, in preparation) will present the fluxes of PACS sources. The PACS images are aligned on the GOODS imaging products. Complementary to the Herschel-PACS observations, we use for this work data from the VLA at 1.4 GHz (Morrison et al. 2010) and Spitzer-MIPS at 24 \(\mu\)m (M. Dickinson et al. 2010, in preparation).

In the past years, several groups surveyed the GOODS-N region using the bolometer cameras SCUBA, AzTEC, and MAMBO (Hughes et al. 1998; Borys et al. 2003; Pope et al. 2005; Wang et al. 2004; Perera et al. 2008; Greve et al. 2008). These observations discovered about 150 SMGs at 850 \(\mu\)m, 1.1 mm, and 1.2 mm. Robustly identified VLA and MIPS 24 \(\mu\)m counterparts are already known in the literature for SCUBA and AzTEC sources (Pope et al. 2006; Chapin et al. 2009). In addition, Greve et al. (2008) presented VLA counterparts for 11 out of 30 MAMBO sources.

We search for Herschel-PACS counterparts of SMGs that are either detected with an S/N of \(\geq 4\) or detected by at least two different surveys. Fifty-six SMGs fulfill this criterion which should assure a robust SMG sample to work with. Our sample consists of 36 SCUBA, 12 AzTEC, and 8 MAMBO sources; and for 15 SMGs, spectroscopic redshifts (SMGspec) have already been obtained. We match our SMG sample with the PACS 100 \(\mu\)m and 160 \(\mu\)m blind catalog and search for counterparts within a radius of \(5\)’\(5\) for MAMBO sources, \(7\)’\(5\) for SCUBA sources, and \(9\)’ for AzTEC sources. As a sanity check of the blind catalog, we inspected by eye the search region in the PACS imaging. The search circles that we have applied correspond to the beam size (FWHM) of the different bolometric data sets and should guarantee that no reliable associations to SMGs will be missed. We also searched the VLA 1.4 GHz map and the MIPS 24 \(\mu\)m images for counterparts at the SMG positions.

We calculate the corrected Poissonian probability \(p\) that an association of SMGs within the search radius is a chance coincidence. This approach (see, for details, Downes et al. 1986) corrects the simple Poissonian probability of a detected association for the possibility of associations of different nature but similar probability. The derived probability of PACS and MIPS association is based on raw number counts in GOODS-N. We search for VLA counterparts of SMGs down to 3\(\sigma\). However, the VLA source catalog (Morrison et al. 2010) is only reliable down to 20 \(\mu\)Jy (\(\sim 5\sigma\)). Therefore, we assess the reliability of VLA counterparts relying on published number counts (e.g., Fomalont et al. 2006). Similar to previous studies, we define following quality criteria for assessing the robustness of identified candidate counterparts. We classify association of SMGs with \(p \leq 0.05\) as secure and with \(0.05 < p \leq 0.10\) as possible counterparts.

We uncover PACS-secure or possible counterparts for 22 SMGs, corresponding to a PACS identification rate of 39% of our whole SMG sample (see Table 1 for details). Our PACS identification rate of 39% is lower than the rate of 54% found by Magnelli et al. (2010). The reason is that Magnelli et al. (2010) focus on already radio-identified SCUBA and AzTEC sources mainly with spectroscopic redshifts. The top panel of Figure 1 displays the (sub)millimeter–PACS separation of our association. We did not find evidence of systematic offsets. We find PACS counterparts at a mean (sub)millimeter–PACS positional offset of \(\Delta_{\text{submm}/\text{mm}} = \Delta_{\text{PACS}100} = 5\)’\(0\) \(\pm 2\)’\(1\) and \(\Delta_{\text{submm}/\text{mm}} = \Delta_{\text{PACS}160} = 4\)’\(9\) \(\pm 2\)’\(0\). This is consistent with a typical submillimeter/millimeter position error of about \(3\)’\(5\) and strengthens our choice of the FWHM of the bolometric data as search circle for PACS counterparts. The top panel of Figure 1 clearly shows a dominance of secure counterparts. Given this statistical approach, associations with offsets much larger than the average might not always be correct.

We detect 20 (16) SMGs at 160 (100) \(\mu\)m and classify 15 (12) of them as secure and 5 (4) as possible counterparts. The number of PACS counterparts at 160 \(\mu\)m is higher than at 100 \(\mu\)m. This is expected as the 160 \(\mu\)m measurements lie close to the FIR peak. We note that based on the corrected Poissonian probability \(p\) each PACS detection within the bolometer beam (our search circle) is classified as an associated SMG counterpart. Typical PACS fluxes of these dust-obscured high-z sources range between 4.0 mJy to 34.9 mJy at 100 \(\mu\)m and 5.0 mJy to 65.0 mJy at 160 \(\mu\)m.

| Table 1 | PACS Associations of 56 Submillimeter Galaxies in GOODS-N |
|---------|-------------------------------------------------------------|
| Sample Characteristics | PACS 100 \(\mu\)m | PACS 160 \(\mu\)m |
| Secure association | 12 | 15 |
| Possible association | 4 | 5 |
| Total identification rate | 28.6% | 35.7% |
| (Sub)millimeter–PACS offset | \(5\)’\(0\) \(\pm 2\)’\(1\) | \(4\)’\(9\) \(\pm 2\)’\(0\) |
| PACS 100 + 160 \(\mu\)m | 22 (39.3%) |
| Only detected at PACS 160 \(\mu\)m | 6 |
| Only detected at PACS 100 \(\mu\)m | 2 |
| New CPTs identified by PACS | 1 |
| PACS and radio blank fields | 12 (21.4%) |

14 In case that an SMG is detected at submillimeter and millimeter bands, we give preference to the SCUBA detection and include it in our sample. For millimeter-only detected sources, we list, if available, the AzTEC otherwise the MAMBO detection.
We have 43 (28 are secure and 15 are possible) radio-identified SMGs in our sample, about 50% of them are seen at PACS wavelengths. Vice versa, only one PACS association (secure) is undetected at 1.4 GHz, see detailed discussion of GN13 (alias HDF850.4) at the end of Section 3. One-third of PACS-detected SMGs have at least two VLA counterparts.

3. DIAGNOSTIC POTENTIAL OF PACS OBSERVATIONS OF SUBMILLIMETER GALAXIES

About twice as many SMGs are identified by the VLA than by PACS. VLA observations are more sensitive for sources at redshifts up to $z = 4$. None of the well-known, spectroscopically identified SMGs at $z = 4$—GN20, GN20.2a/b, and GN10 (Daddi et al. 2009a, 2009b; Wang et al. 2007, 2009; Dannerbauer et al. 2008)—have been significantly detected in our PACS imaging (see the middle panel of Figure 1). Another highly promising $z \geq 4$ candidate, HDF850.1 (Hughes et al. 1998; Dunlop et al. 2004; Cowie et al. 2009) is also not seen by PACS. However, all of these SMGs have radio counterparts. Focusing on our spectroscopic subsample of 15 sources, SMG$_{\text{spec}}$, we find a trend that the fraction of SMGs detected at PACS bands decreases with redshift (see the middle panel of Figure 1), being explained by the fact that PACS fluxes drop with increasing redshift. No source beyond $z = 2.00$ (GN06) at 100 $\mu$m and $z = 2.58$ (GN04) at 160 $\mu$m is significantly detected by PACS. However, we do not find evidence that the PACS detection rate of SMGs correlates with the SCUBA flux density (Figure 1). In addition, VLA observations provide subarcsecond-accurate positions which are essential for the proper identification in the optical and near-infrared bands and follow-up spectroscopic observations. PACS cannot deliver positions at these accuracies. To summarize, ultra-deep VLA observations still remain the best and most effective approach to identify SMG counterparts, even up to redshift $z = 4$.

Using only radio, 850 $\mu$m and 24 $\mu$m flux densities, Daddi et al. (2009b) derived accurate ($\Delta z/(1 + z) \sim 0.1$) radio–IR photometric redshifts for SMGs. Motivated by this work, we apply the radio–IR photometric redshift code presented in Daddi et al. (2009b) and calculate photometric redshifts by adding our PACS measurements to existing SCUBA, MIPS 24 $\mu$m, and VLA 1.4 GHz flux measurements of our SMG sample. Naively, we would have expected to improve the accuracy of the radio–IR photometric redshifts by adding FIR measurements shortward to the IR dust peak. In Figure 2, we show the results of our attempt using template libraries of local galaxies (Chary & Elbaz 2001). In the left panel, we show photometric redshifts (adapted from Daddi et al. 2009b) based on radio, MIR, and submillimeter observations for SCUBA counterparts with known spectroscopic redshifts in GOODS-N which agree fairly well. In the right panel, we show photometric redshift estimates adding the PACS measurements to our previous measurements in the radio, MIR, and submillimeter. Clearly, the obtained accuracy decreases and these photo-$z$ estimates are poorer. Omitting certain measurements (e.g., MIPS 24 $\mu$m and/or VLA 1.4 GHz) gives even worse results. We obtain similar results by using template libraries from Dale & Helou (2002) and the average SED constructed by Michalowski et al. (2010) of 73 spectroscopically identified SMGs (Chapman et al. 2005). This result means that most likely the far-infrared properties of SMGs are different from templates built to describe local galaxies. These observed differences arise most probably from the fact that SMGs are colder than local ULIRGs of same luminosity (Chapman et al. 2005; Magnelli et al. 2010; Elbaz et al. 2010; P. Chanial et al. 2010, in preparation). Further investigations are needed to fully exploit the Herschel-PACS imaging in order to obtain accurate photometric redshifts.

Figure 1. Top panel: histogram of distance between the submillimeter/millimeter position from the bolometric map and PACS positions of associated FIR sources at 100 $\mu$m (left) and 160 $\mu$m (right). Black and gray indicate secure and possible PACS counterparts. Middle panel: we show the redshift distribution for our SMG sample with spectroscopic redshifts (gray) and overplot our PACS detections at 100 $\mu$m (green) and 160 $\mu$m (red), respectively. Lower panel: we show the SCUBA flux distribution of our SMG sample (gray) and overplot our PACS-detected SMGs have at least two VLA counterparts.

Figure 2. Comparison of spectroscopic and photometric redshifts. In the left panel, we show photometric redshifts based on radio, 850 $\mu$m and 24 $\mu$m flux densities measurements for SMG counterparts with spectroscopic redshifts in GOODS-N (adopted from Daddi et al. 2009b). There is a fairly good agreement. In the right panel, we show photometric redshift estimates including PACS measurements which are less reliable.
We already know the spectroscopic redshift for 15 SMGs in our sample. However, in absence of spectroscopic redshifts for most of our sources, searching for correlations between observed properties is essential for constraining the nature, redshift, and evolution of SMGs. We explore if flux ratios involving PACS 100 μm and 160 μm measurements can be used as a rough redshift indicator. Figure 3 displays the results of our analysis. The PACS color (S_{160}/S_{100}) of SMGs does not vary with redshift and is consistent with the prediction of models and observed SEDs from Chary & Elbaz (2001), Michałowski et al. (2010), and Pope et al. (2008). The PACS colors seem to be slightly redder than predicted by the various models and may indicate a difference between the observed FIR-SED of SMGs and templates describing fairly well local infrared galaxies. The composite rest-frame SED for the SMGspec (Figure 3) subsample shows their diversity in redshift for the SMGspec subsample over the whole redshift range spanned by our SMGs from z ~ 1–4. We conclude that the (sub)millimeter/PACS flux ratio seems to be a useful albeit crude redshift indicator and may help to select/mark SMGs at very high redshifts. We also explored VLA/PACS and PACS/MIPS 24 μm flux ratios versus redshift but did not observe any correlation, being consistent with the fact that VLA, MIPS 24 μm, and PACS fluxes drop with increasing redshift. Based on this finding, we investigate the (sub)millimeter/PACS ratio for the remaining 41 SMGs without any reliable redshift. This analysis shows that PACS-detected SMGs tend to have lower flux ratios than the PACS-undetected SMG sample (Figure 3). This trend seems to be more prominent for the S_{850}/S_{160} flux density ratio. Our analysis may indicate that, indeed, as previously discussed, PACS-undetected SMGs could tend to lie at higher redshifts and the (sub)millimeter/PACS flux ratio could be a crucial tool to select the very high-z tail of the SMG population.

The previous analysis bridges with the discovery that 12 out of 56 SMGs (21%) in our sample are blank fields both at PACS and radio wavelengths. The nature of these sources is still not clear.

For SCUBA sources from Pope et al. (2006), we use the deboosted flux. The same we do for AzTEC and MAMBO sources. We converted the AzTEC and MAMBO millimeter flux densities into SCUBA flux densities by assuming a flux ratio of S_{850}/S_{100} of 2.5 for a ULIRG-like SED at redshift z ~ 2–3.
These SMGs could be either spurious sources, which is mainly assumed, or at redshifts higher than \( z > 4 \). It is worthwhile to ask: how reliable are these (sub)millimeter sources detections? The sample consists of seven submillimeter and five millimeter selected sources (of the latter population, one is seen by AzTEC and four by MAMBO). We checked each source for its reliability. The millimeter sources are selected with \( S/N \gtrsim 4 \). Four of the seven SCUBA galaxies are listed in both Pope et al. (2006) and Wang et al. (2004). The fact that Pope et al. (2006) and Wang et al. (2004) used (nearly) the same SCUBA data, but performed independent data reduction and source extraction, is giving more weight to the reliability of these detections. As a sanity check, we inspected the SCUBA and MAMBO galaxies in the AzTEC 1 mm map. Our analysis suggests that most of these sources are reliable. One of them has an \( S/N \sim 9 \) at 850 \( \mu \)m. However, we note that only millimeter interferometric observations will reveal unambiguously the reliability of these sources. Their non-detection both at radio and PACS wave bands in combination with its (sub)millimeter/PACS flux ratio may suggest that these sources could lie at higher redshifts than the typical SMG population (e.g., \( z > 3-4 \)).

We conclude this work by presenting the identification of an SMG counterpart having a PACS but no VLA detection. Daddi et al. (2009b) suspected that the counterpart at \( z \approx 0.457 \), about 7′′ away from the SCUBA position, could not be the correct counterpart of GN13 alias HDF850.4 (Pope et al. 2006; Hughes et al. 1998). We detect a faint (4.2σ), secure counterpart at 100 \( \mu \)m (see Figure 4), being very close to the bolometer position (\( \sim 0′.6 \)). Its reliability is fortified by a 200 \( \mu \)Jy strong, secure counterpart at 24 \( \mu \)m. Using the flux ratios \( S_{850 \mu m}/S_{100 \mu m} = 0.38 \) and \( S_{850 \mu m}/S_{160 \mu m} > 0.37 \) as a coarse redshift indicator suggests a redshift of \( z \sim 1-2.5 \).

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