Dissecting the cosmic infra-red background with Herschel/PEP**

S. Berta1, B. Magnelli1, D. Lutz, B. Altieri2, H. Aussel3, P. Andreani4,5, O. Bauer1, A. Bongiovanni6,7, A. Cava6,7, J. Cepa6,7, A. Cimatti8, E. Daddi9, H. Dominguez9, D. Elbaz, H. Feuchtgruber1, N. M. Förster Schreiber, R. Genzel1, C. Gruppioni9, R. Katterloher1, G. Magdis, R. Maiolino10, R. Nordon1, A. M. Pérez García6,7, A. Poglitsch1, P. Popesso1, F. Pozzi9, L. Riguccini9, G. Rodighiero11, A. Saintonge1, P. Santini10, M. Sanchez-Portal2, L. Shao1, E. Sturm1, L. J. Tacconi1, I. Valtchanov2, M. Wetzstein1, and E. Wieprecht1

(Affiliations are available in the online edition)

Received 31 March 2010 / Accepted 21 April 2010

ABSTRACT

The constituents of the cosmic IR background (CIB) are studied at its peak wavelengths (100 and 160 μm) by exploiting Herschel/PACS observations of the GOODS-N, Lockman Hole, and COSMOS fields in the PACS evolutionary probe (PEP) guaranteed-time survey. The GOODS-N data reach 3σ depths of ~3.0 mJy at 100 μm and ~5.7 mJy at 160 μm. At these levels, source densities are 40 and 18 beams/source, respectively, thus hitting the confusion limit at 160 μm. Differential number counts extend from a few mJy up to 100-200 mJy, and are approximated as a double power law, with the break lying between 5 and 10 mJy. The available ancillary information allows us to split number counts into redshift bins. At z ≤ 0.5 we isolate a class of luminous sources (LIR ≈ 1011 L⊙), whose SEDs resemble late-spiral galaxies, peaking at ~130 μm restframe and significantly colder than what is expected on the basis of pre-Herschel models. By integrating number counts over the whole covered flux range, we obtain a surface brightness of 6.36 ± 1.67 and 6.58 ± 1.62 [nW m^2 sr^-1] at 100 and 160 μm, resolving ~45% and ~52% of the CIB, respectively. When stacking 24 μm sources, the inferred CIB lies within 1.1σ and 0.5σ from direct measurements in the two bands, and fractions increase to 50% and 75%. Most of this resolved CIB fraction was radiated at z ≤ 1.0, with 160 μm sources found at higher redshift than 100 μm ones.

Key words. infrared: diffuse background – infrared: galaxies – cosmic background radiation – galaxies: statistics – galaxies: evolution

1. Introduction

The cosmic IR background (CIB, Puget et al. 1996; Hauser et al. 1998) accounts for roughly half of the total extragalactic background light (EBL, Hauser & Dwek 2001; Lagache et al. 2005), i.e., half of the energy radiated by all galaxies, at all cosmic epochs, at any wavelength (Dole et al. 2006). It is therefore a crucial constraint on modes and times of galaxy formation. Deep cosmological surveys carried out with the ISO (see Genzel & Cesarsky 2000, for a summary) and Spitzer Space Observatory (Soifer et al. 2008, for a review) produced large samples of mid-IR sources and deep number counts (Elbaz et al. 2002; Papovich et al. 2004). These surveys led to mid-IR CIB lower limits within a factor of two from the upper constraints set by TeV cosmic opacity measurements (e.g. Franceschini et al. 2010). However, at CIB peak wavelengths (100–200 μm), the nature of individual galaxies building up the EBL is poorly known. Past surveys produced limited samples of distant far-IR objects (e.g. Frayer et al. 2009), mainly due to the small apertures of the available instruments and the low sensitivity in the far-IR. In the 160 μm Spitzer/MIPS band, ~7% of the CIB was resolved into individually detected objects (Dole et al. 2004), and it was only through stacking the 24 μm sources that most (60–70%) of the far-IR CIB could be recovered (Dole et al. 2006; Béthermin et al. 2010). Similarly, at longer wavelengths, only stacking of 24 μm sources on BLAST maps could account for the majority of the EBL at 250, 350, and 500 μm (Marsden et al. 2009).

With the favorable diffraction limit of the large Herschel 3.5 m mirror (Pilbratt et al. 2010), and the high sensitivity of its Photodetector Array Camera and Spectrometer (PACS, 70, 100, 160 μm; Poglitsch et al. 2010), confusion and blending of sources are much less of a limitation. We are now able to resolve a large fraction of the CIB at its peak into individual galaxies. The PACS evolutionary probe (PEP) extragalactic survey samples 4 different tiers: from the wide and shallow COSMOS field, through medium size areas like the Lockman hole, all the way down to the 160 and 100 μm confusion limit in the pencil-beam, very deep observations in GOODS-N and GOODS-S, and even beyond by exploiting gravitational lensing in low-redshift galaxy clusters (e.g. Abell 2218; Altieri et al. 2010). Here we exploit the science demonstration phase (SDP) observations of the GOODS-N field, complemented with the COSMOS and Lockman hole (LH) wider and shallower layers of the survey, to build far-IR galaxy number counts and derive the fraction of CIB resolved by PEP. We then take advantage of the extensive multi-wavelength coverage of the GOODS-N field, with the aim of identifying the CIB contributors and the epoch when the bulk of the Universe IR energy budget was emitted.

2. Number counts

The area used to derive number counts includes observations in the GOODS-N (~140 arcmin^2), COSMOS (~2 deg^2) and LH...
Insets mark the trends expected for a non-evolving population of galaxies. Consequently, the large uncertainties allow for nearly-Euclidean fields is low, and error bars are dominated by Poisson statistics. At the bright end, the number of sources in the small fields is low, and error bars are dominated by Poisson statistics.

Small insets in Fig. 1 show results from PACS guaranteed-time surveys: this work, Abell 2218 lensed counts (Altieri et al. 2010), and HerMES (Aussel et al., in prep.). The three datasets complement each other and show overall agreement, the 160 μm slope derived from our counts (GOODS-N only) is consistent with what is found by stacking 24 μm sources on Spitzer 160 μm maps (Béthermin et al. 2010, α = −1.61 ± 0.21).

3. Resolved CIB fraction

The added contribution of resolved galaxies provides a lower limit to the IR background and can be compared to direct measurements of the total CIB. After the discovery of the CIB (Puget et al. 1996; Hauser et al. 1998), numerous authors attempted to directly measure its surface brightness from COBE/DIRBE maps (e.g. Lagache et al. 2000; Renault et al. 2001; Wright 2004; Dole et al. 2006). Here we adopt the most recent revision of the Lagache et al. (2000) DIRBE measurements, provided in Dole et al. (2006): 14.4 ± 6.3, 12.0 ± 6.9, and 12.3 ± 2.5 [nW m⁻² sr⁻¹], at 100, 140, and 240 μm, respectively. Interpolating between these values, one obtains a value of 12.8 ± 6.4 [nW m⁻² sr⁻¹] at 160 μm. These direct measurements are still affected by large uncertainties, mainly due to difficulties in defining an absolute flux scale and in removing zodiacal light. An alternative estimate of the total CIB is obtained by integrating the power-law extrapolation of our number counts, between 0.01 and 1000 mJy. We adopt the slope derived on GOODS-N data for the IR galaxy population (see Sect. 4): the trend expected for no-evolution is shown in Fig. 1 insets.
(100 μm) and red (160 μm) bands, within the errors of the direct measurements.

The contribution to the CIB of individual GOODS-N sources detected above 3σ is \( n_L = 4.46 \pm 0.52 \) at 100 μm and \( 4.41 \pm 0.62 [nW ~ m^{-2} ~ sr^{-1}] \) at 160 μm, i.e., \( \sim 31 \pm 4\% \) and \( \sim 35 \pm 5\% \) of the direct DIRBE measurements (Fig. 2). Taking the effects of completeness into account (see Sect. 2), we can compute the CIB fraction due to the general FIR-population, overriding source extraction losses. We limit the analysis to the 3σ detection limit again. The GOODS-N number counts cover the ranges 3–45 mJy (at 100 μm) and 5.5–72 mJy (at 160 μm); the COSMOS field allows upper boundaries to be extended to 142 and 179 mJy. Integrating the counts over the whole flux range, we obtain \( n_L = 6.36 \pm 1.67 \) and \( 6.58 \pm 1.62 [nW ~ m^{-2} ~ sr^{-1}] \), within 1.3σ and 1.0σ from the reference values at 100 and 160 μm, respectively (Fig. 2). These correspond to \( \sim 45 \pm 12\% \) and \( \sim 52 \pm 13\% \) of the Dole et al. (2006) estimate. The derived uncertainty now also includes the effect of Poisson statistics and not only photometric errors. The bright end of number counts, covered only by COSMOS, gives a small contribution (\( \sim 4–6\% \)) to the total CIB surface brightness.

The PACS detection rate of Spitzer 24 μm sources (\( S_{24} \geq 20 \) μJy, Magnelli et al. 2009) is roughly 15%. It is possible to derive a deeper CIB estimate, through stacking on the PEP maps at the positions of all 24 μm objects, including those not detected in the FIR (e.g. Dole et al. 2006). Uncertainties on the stacked fluxes are computed via a simple bootstrap procedure. The CIB surface brightness produced by 24 μm sources is \( 7.39 \pm 0.48 \) and \( 9.57 \pm 0.71 [nW ~ m^{-2} ~ sr^{-1}] \) at 100 and 160 μm, consistent with Béthermin et al. (2010), and providing \( \sim 51\% \) and \( \sim 75\% \) of the total background, within 1.1σ and 0.5σ from Dole et al. (2006).

4. Discussion

In the attempt to reproduce the observed ISO and Spitzer number counts, several authors built “backward” evolutionary models, including luminosity and/or density evolution, as well as different galaxy populations. In Fig. 1, we overlay recent models onto the observed PACS counts. We include in this collection the Lacey et al. (2010) Λ-CDM semi-analytical model (SAM), complemented with radiative transfer dust reprocessing. The most successful models are the Valiante et al. (2009), including luminosity-dependent distribution functions for the galaxy IR SEDs and their AGN contribution, and Rowan-Robinson (2009), employing analytic evolutionary functions without discontinuities and 4 galaxy populations.

Gruppioni and Lagache (2004) overestimate the amplitude of the number counts peak in both bands, while Franceschini et al. (2010) and Le Borgne et al. (2009) reproduce the counts fairly well only in one channel (100 and 160 μm, respectively). It is worth recalling that to date most of these models have been fine-tuned to reproduce mid-IR and sub-mm statistics, while a big gap in wavelength was affecting far-IR predictions. Most include a luminosity evolution \( \alpha = (1 + z)^{\beta} \), but the redshift limit for this slope, the details of density evolution, or the adopted galaxy zoo vary significantly from author to author.

Besides spanning a much wider range of observational data (UV, optical, near-IR luminosity functions, galaxy sizes, metallicity, etc.), the SAM approach suffers here for a limited flexibility in the choice of parameters, and significantly overestimates the bright end of PACS counts. Moreover, it cannot reproduce the peak, especially in the green band.

Thanks to the rich ancillary dataset in GOODS-N, we split the far-IR number counts into redshift bins (Fig. 3). This elaboration offers a remarkable chance to set detailed constraints on the evolution of the galaxy populations adopted in current recipes. This view highlights some new features and the main problems of the models under discussion.

First, in the lowest redshift bin, 0.0 \( < z \leq 0.5 \), the differential number counts, normalized to the Euclidean slope, monotonically increase as a function of flux, resembling the trend expected for a non-evolving population of galaxies. The consistency of models with data weakens at longer wavelengths. At the bright end, above 10 mJy and 20 mJy at 160 μm, PEP catalogs include 43 and 18 objects in this redshift range. Based on template fitting (Rodighiero et al. 2010), half of this sample shows a late-spiral SED (\( S_{\lambda, Sdm} \) in the Polletta et al. 2007, template library) with typical luminosities above \( 10^{11} L_{\odot} \) and a peak wavelength of \( \sim 130 \) μm. Nevertheless, at these luminosities, Chary & Elbaz (2001) models, which adopt the local \( L \sim T \) relation, predict SEDs peaking around 90 μm, which is rather colder than typical local IR-luminous sources. This is reminiscent of the cold sources found by ISO FIRBACK and serendipity surveys (e.g. Deinsefeld et al. 2005; Stickel et al. 2007).

Significant differences between models arise at higher redshift. The bin 1.0 \( < z \leq 2.0 \) shows the largest discrepancies: apparently, most of the overestimation of total number counts by some models originates here, suggesting that the adopted evolution is either too protracted in time or too steep.

We are now able for the first time to infer how much of the resolved CIB peak was emitted at different cosmic epochs. Figure 2 depicts the amount of extragalactic IR background originating from the four redshift bins taken into account (see also Fig. 3). At 100 μm, at the GOODS-N 3σ limit of \( \sim 3 \) mJy, roughly 80% of the resolved CIB is emitted by objects detected.
Fig. 3. Slicing the PEP GOODS-N population into redshift bins. Each PACS source has been associated to an optical/mid-IR counterpart as described in Appendix A. See Fig. 1 and text for details on the models shown.

at \( z \leq 1 \), equally distributed below and above \( z = 0.5 \). The remainder belongs to more distant galaxies, with only 5% locked into individual objects at \( z > 2 \). Most of the resolved 160 \( \mu \)m CIB is produced at higher redshift, with the 0.5 < \( z \leq 1 \) redshift bin dominating (~40%) the budget. At the PEP depth, the CIB resolved into individual sources is mainly due to luminous and ultraluminous IR galaxies (LIRGs \( 10^{11} \leq L_{\text{IR}} < 10^{12} L_{\odot} \), ULIRGs \( L_{\text{IR}} \geq 10^{12} L_{\odot} \)). The relative fraction of the two classes varies as a function of redshift, likely due to selection effects, with LIRGs providing 80–90% of the CIB resolved at \( 0.5 < z \leq 1 \) and ULIRGs dominating at higher redshift (60–70% at \( 1 < z \leq 2 \) and 100% above).

Finally, Fig. 2 also reports the CIB contribution of 24 \( \mu \)m sources, as obtained through stacking (see Sect. 3). The relative CIB fractions emitted in the four redshift bins change significantly at 100 \( \mu \)m, with respect to those obtained by integrating the observed counts. The redshift distribution of the CIB is now peaking between 0.5 < \( z < 1 \) and the relative contribution of \( z > 1 \) increases by more than 10%. On the other hand, at 160 \( \mu \)m only the relative fraction of the highest redshift bin varies by more than 5%, while the others remain unchanged within 1–2%. Also in the case of stacking, the 160 \( \mu \)m CIB relative redshift distribution is more populated at high redshift than the 100 \( \mu \)m one. As expected, this indicates that PACS galaxies with redder observed colors lie on average at higher redshift than bluer ones.

Acknowledgements. PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KU Leuven, CSL, IMEC (Belgium); CEA, LAM (France); MPIA (Germany); INAF-IFSI/OAA/OAP/OAT, LENS, SISSA (Italy); IAC (Spain). This development has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI/INAF (Italy), and CICYT/MCYT (Spain).

References

Altieri, B., et al. 2010, A&A, 518, L17
Barger, A. J., Cowie, L. L., & Wang, W. 2008, ApJ, 689, 687
Béthermin, M., Dole, H., Beelen, A., & Aussel, H. 2010, A&A, 512, A78
Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, ApJ, 686, 1503
Chary, R., & Elbaz, D. 2001, ApJ, 556, 562
Chary, R., & Elbaz, D. 2001, ApJ, 556, 562
Chary, R., Casertano, S., Dickinson, M. E., et al. 2004, ApJS, 154, 80
Dennfeld, M., Lagache, G., Mei, S., et al. 2005, A&A, 440, 5
Diolaiti, E., Bendinelli, O., Bonacini, D., et al. 2000, A&A, 347, 335
Dole, H., Lagache, G., & Puget, J. L. 2003, ApJ, 585, 617
Dole, H., Le Floc’h, E., Pérez-González, P. G., et al. 2004, ApJS, 154, 87
Dole, H., Lagache, G., & Puget, J. L. 2006, A&A, 451, 417
Elbaz, D., Cesarsky, C. J., Chabrier, P., et al. 2002, A&A, 384, 848
Fuxion, D., Dwek, E., Mathier, J., Bennett, C., & Shafer, R. 1998, ApJ, 508, 123
Franceschini, A., Rodighiero, G., Vaccari, M., et al. 2010, A&A, in press [arXiv:0906.4264]
Frayer, D. T., Sanders, D. B., Surace, J. A., et al. 2009, AJ, 138, 1261
Fruchter, A. S., & Hook, R. N. 2002, PASP, 114, 144
Genzel, R., & Cesarsky, C. J. 2000, ARA&A, 38, 761
Giavalisco, M., Ferguson, H. C., Koekemoer, A. M., et al. 2004, ApJ, 600, L93
Grazian, A., Fontana, A., de Santis, C., et al. 2006, A&A, 449, 951
Hauser, M. G., & Dwek, E. 2001, ARA&A, 39, 249
Hauser, M. G., Arden, R. G., Kelsall, T., et al. 1998, ApJ, 508, 29
Héraudeau, P., Oliver, S., del Burgo, C., et al. 2004, MNRAS, 354, 924
Lacey, C. G., Baugh, C. M., Frenk, C. S., et al. 2010, MNRAS, 405, 2
Lagache, G., Abergel, A., Boulanger, F., Désert, & Puget. 1999, A&A, 344, 322
Lagache, G., Haffner, L., Reynolds, R., & Tuttle, S. 2000, A&A, 354, 247
Lagache, G., Dole, H., & Puget, J. L. 1998, ApJ, 508, 29
Lagache, G., Dole, H., Puget, J. L., et al. 2004, ApJS, 154, 112
Lagache, G., Puget, J., & Dole, H. 2005, A&A, 43, 727
Le Borgne, D., Elbaz, D., Ocvirk, P., & Pichon, C. 2009, A&A, 504, 577
Magnelli, B., Elbaz, D., Chary, R. R., et al. 2009, A&A, 496, 57
Marsden, G., Ade, P. A. R., Bock, J. J., et al. 2009, ApJ, 707, 1729
Ott, S., et al. 2010, ASP Conf Series, ADASS XIX, Mizumoto et al. eds, in press
Owen, F. N., & Morrison, G. E. 2009, ApJS, 182, 625
Papovich, C., Dole, H., Egami, E., et al. 2004, ApJS, 154, 70
Pilbratt, G. L., et al. 2010, A&A, 518, L1
Poglitsch, A., et al. 2010, A&A, 518, L2
Polletta, M., Tajer, M., Maraschi, L., et al. 2007, ApJ, 663, 81
Puget, J., Abergel, A., Bernard, J., et al. 1996, A&A, 308, L5
Renault, C., Barrau, A., Lagache, G., & Puget, J. 2001, A&A, 317, 771
Rodighiero, G., & Franceschini, A. 2004, A&A, 419, L55
Rodighiero, G., et al. 2010, A&A, 518, L25
Rowan-Robinson, M. 2009, MNRAS, 394, 117
Soifer, B. T., Helou, G., & Werner, M. 2008, ARA&A, 46, 201
Starck, J., & Murtagh, F. 1998, PASP, 110, 144
Stickel, M., Klaas, U., & Lemke, D. 2007, A&A, 466, 831
Sutherland, W., & Saunders, W. 1992, MNRAS, 259, 413
Valiante, E., Lutz, D., Sturm, E., Genzel, R., & Chapman, E. 2009, ApJ, 701, 1814
Wright, E. L. 2004, New Astron. Rev., 48, 465
Table 1. PEP number counts, normalized to the Euclidean slope.

| $S_{\text{center}}$ | GOODS-N 100 μm | LH 100 μm | COSMOS 100 μm | GOODS-N 160 μm | LH 160 μm | COSMOS 160 μm |
|---------------------|----------------|-----------|----------------|----------------|-----------|----------------|
| 2.84                | 3.19e+04      | 0.208     | 2.66e-06       | 1.17e+05       | 0.129     | 6.81e-06       |
| 3.57                | 4.67e+04      | 0.146     | 6.68e-07       | 1.34e+05       | 0.142     | 7.15e-07       |
| 4.50                | 5.57e+04      | 0.149     | 7.15e-08       | 1.42e+05       | 0.173     | 7.15e-08       |
| 5.66                | 6.37e+04      | 0.162     | 7.00e+04       | 1.17e+05       | 0.129     | 6.58e-06       |
| 7.13                | 6.90e+04      | 0.185     | 7.22e+04       | 1.34e+05       | 0.142     | 6.37e-06       |
| 8.97                | 6.43e+04      | 0.234     | 6.58e+04       | 1.42e+05       | 0.173     | 1.11e-06       |
| 11.30               | 6.29e+04      | 0.287     | 7.24e+04       | 1.17e+05       | 0.129     | 6.58e-06       |
| 14.22               | 6.81e+04      | 0.333     | 8.13e+04       | 1.34e+05       | 0.142     | 6.37e-06       |
| 17.91               | 1.11e+05      | 0.302     | 7.00e+04       | 1.17e+05       | 0.129     | 6.58e-06       |
| 22.54               | 8.13e-04      | 0.443     | 6.66e+04       | 1.34e+05       | 0.142     | 6.37e-06       |
| 28.38               | 1.11e+05      | 0.438     | 6.70e+04       | 1.34e+05       | 0.142     | 6.37e-06       |
| 35.73               | 6.63e-04      | 0.701     | 4.01e+04       | 1.34e+05       | 0.142     | 6.37e-06       |
| 44.98               | 6.68e-04      | 0.814     | 5.97e+04       | 1.34e+05       | 0.142     | 6.37e-06       |
| 56.62               | –              | –         | 1.81e+04       | 1.000          | 0.333     | 6.58e-06       |
| 71.29               | –              | –         | 2.40e+04       | 1.000          | 0.333     | 6.58e-06       |
| 89.74               | –              | –         | 8.46e+04       | 0.655          | 0.333     | 6.58e-06       |
| 112.98              | –              | –         | 2.51e+04       | 0.453          | 0.333     | 6.58e-06       |
| 142.23              | –              | –         | 3.81e+04       | 0.412          | 0.333     | 6.58e-06       |
| 179.06              | –              | –         | –              | –              | 0.333     | 6.58e-06       |

Notes. Fluxes are provided in [mJy]. For each field/wavelength, we list counts in units of [deg$^{-2}$ mJy$^{-1}$]. Errors are given as relative fractions, and include both Poisson statistics and propagation of photometric uncertainties.

Appendix A: PACS data

PEP science demonstration data include the GOODS-N and Abell 2218 fields. In addition to these, part of the other PEP blank fields have already been scheduled and observed: Lockman Hole and COSMOS ($\sim$85% of the planned depth). Observations of all fields were carried out by adopting the intermediate speed (20 arcsec/s) scan-map mode. Table A.1 lists the total exposure times already observed for these fields.

Data have been processed through the standard PACS reduction pipeline, version 2.0.1328, within the HCSS environment (Ott et al. 2010). Additionally, we employed custom procedures aimed at removing of interference patterns, tracking anomalies, re-centering positional offsets, and mapping.

Glitch removal is based on multi-resolution median transform, developed by Stark & Murtagh (1998) to detect faint sources in ISOCAM data. The signal due to real sources and glitches show different signatures in the pixel timeline. These features are recognized using a multi-scale transform, separating the various frequencies of the signal. Once the glitch components are identified, they are replaced by interpolated values in the pixel timeline.

PACS photometers exhibit a noise with a roughly $f^{-0.5}$ spectrum at relevant frequencies. To remove the bulk of the noise we apply a “running-box” high-pass median filter to each pixel timeline, but mask the position of bright sources. The objects mask is produced iteratively during the reduction by detecting sources on the final map, and then we mask them in a double-pass mapping scheme. Testing shows that this masked filtering method modifies the fluxes of point-like source by less than 5%.

Imperfections, drifts, and errors in the pointing accuracy of the Herschel satellite were corrected by re-centering the data on a grid of known 24 μm sources populating the fields. Such objects were stacked for all scan-legs in a given direction in a given map repetition (or for a subset of those, in the very large COSMOS maps). The stacking result was then used to compute the average offset to be applied to this set of scan-legs, for a given direction, in a given map repetition. This procedure also implicitly corrects for small timing offsets between pointing information and data. Absolute, systematic astrometric offsets turned out to be as high as 5 arcsec, while relative corrections between individual submaps are approximately 1 arcsec.

Map reconstruction is done via simple image co-addition, based on a simplified version of the “drizzle” method (Fruchter & Hook 2002). Given the high data redundancy in the GOODS-N field, the drop size is set to 1/8 of the input array pixel size. This corresponds to 1/5 and $\sim$1/4 of the output pixel size at 100 μm and 160 μm, respectively, thus reducing the correlated noise in the final map. Fields with lower redundancy were mapped by adopting a smaller drop size (1/4 of the input PACS array pixel size). Images produced from each observation were weighted according to the effective exposure of each pixel and co-added to produce the final maps. The final error map was computed as the standard deviation of the weighted mean. Owing to the nature of scan maps, correlations exist between nearby pixels, in particular along the scan direction. These correlations are close to uniform across the final map, thus we derived a mean correlation correction factor which was then accounted for in the errors on the extracted fluxes.

PACS catalogs were extracted following two different approaches, optimized for the different scientific aims of the PEP project. We performed a blind extraction using the Starfinder PSF-fitting code (Dolaiti et al. 2000) and a guided extraction using 24 μm priors, following the method described in Magnelli et al. (2009). The two methods provide similar results: fluxes extracted in the two cases are consistent with each other, the

1 See the PEP web page for information about the other fields in the survey: http://www.mpe.mpg.de/ir/Research/PEP/.

2 HCSS is a joint development by the Herschel Science Ground Segment Consortium, consisting of ESA, the NASA Herschel Science Center, and the HIFI, PACS and SPIRE consortia.
prior extraction leading to slightly deeper – although possibly biased – catalogs. The number counts presented in this paper were based on the blind catalog. Point spread function (PSF) profiles were extracted from the final science maps, and turn out to have an FWHM of \( \sim 7.5 \) and \( \sim 11 \) arcsec in the 100 \( \mu m \) and 160 \( \mu m \) bands, respectively. Aperture corrections were characterized on calibration observations of the Vesta asteroid. Absolute flux calibration is based on the Grazian et al. (2006) PSF-matched database, including ACS bands, respectively. Aperture corrections were characterized on calibration observations of the Vesta asteroid. Absolute flux calibration is based on the Grazian et al. (2006) PSF-matched database, including ACS bands, respectively.

Noise in PACS maps was measured with random aperture extractions on residual images and compared to the observed S/N ratio for the detected sources. The rms values thus obtained include both instrumental noise and confusion noise due to undetected sources (i.e., below the 3\( \sigma \) threshold). This measured 1\( \sigma \) noise is 1.00 mJy at 100 \( \mu m \) and 1.90 mJy at 160 \( \mu m \) for GOODS-N. Table A.1 includes the noise properties of the SDP fields, as well as the Lockman Hole and COSMOS.

To quantify the reliability of extracted fluxes, the level of incompleteness and the fraction of spurious sources, Monte Carlo simulations were performed, creating 500 images and adding 20 artificial objects onto science maps each, for a total of 10,000 sources. Input and output fluxes are consistent with each other within a few percent. Completeness is defined as the fraction of sources that have been detected with a photometric accuracy of at least 50% (Papovich et al. 2004). Spurious sources are defined as those extracted above 3\( \sigma \) with an input flux lower than 3\( \sigma \) (Image). The latter is consistent with the spurious fraction inferred by blindly extracting from inverted maps. The GOODS-N blind catalog reaches 80% completeness at \( \sim 5.5 \) mJy and \( \sim 11.0 \) mJy in the two bands, and a 30% fraction of spurious detections at \( \sim 2.5 \) and \( \sim 7.0 \) mJy, in green and red respectively (see Table A.1).

The GOODS-N field benefits from an extensive multi-wavelength coverage. Adopting the Grazian et al. (2006) approach, the PEP Team built a reliable multi-wavelength, PSF-matched database, including ACS data (Giavalisco et al. 2004), Flamingos JHK and Spitzer IRAC data. Moreover, MIPS 24 \( \mu m \) (Magnelli et al. 2009) and Barger et al. (2008) deep U, KS, and spectroscopic redshifts have been added. When no spectroscopic redshifts were available, photometric redshifts have been derived using the EAZY code (Brammer et al. 2008).

The 100 and 160 \( \mu m \) blind catalogs were finally linked to this multi-wavelength catalog through a three-band maximum likelihood procedure (Sutherland & Saunders 1992), starting from the longest wavelength available (160 \( \mu m \), PACS) and progressively matching 100 \( \mu m \) (PACS) and 24 \( \mu m \) (Spitzer/MIPS) data. Table A.1 summarizes the main properties of blind catalogs, as well as the results of the maximum-likelihood match in GOODS-N.

Confusion is a major concern in deep wide-beam observations, like far-IR or sub-mm imaging of blank fields. PEP Herschel observations are not dispersed from confusion: the high density of detected sources hinders the extraction of fainter objects, in the so-called “source density confusion criterion” (SDC, Dole et al. 2003). Adapting the Lagache et al. (2003) definition of beam (i.e., \( \Omega = 1.14 \times \theta_{FWHM}^2 \)), the source density in PACS blind catalogs is 40 beams/source at 100 \( \mu m \) and 18 beams/source at 160 \( \mu m \). This indicates that PEP GOODS-N is already hitting the SDC limit in the PACS red band, estimated to be 16.7 beams/source by Dole et al. (2003), while the green channel is not affected. By extrapolating integral number counts, we estimate that this limit will be reached at \( \sim 2.0 \) mJy at 100 \( \mu m \) and \( \sim 4.7 \) mJy at 160 \( \mu m \). Nevertheless, this limit is known to be rather conservative, and some authors have already shown that source extraction can be reliably carried out to levels as low as 10 beam/source under favorable conditions (e.g. at 24 \( \mu m \), Magnelli et al. 2009).

---

**Table A.1.** PEP fields: total exposure times, noise properties, flux levels for 80% completeness and 30% spurious fraction, statistics of blind catalogs, and results of maximum-likelihood match to the multi-wavelength ancillary catalogs (labeled “multi”, GOODS-N only).

| Field & band | Area [arcmin²] | Exposure [h] | rms [mJy] | N(PACS) >3\( \sigma \) | Compl. [80%] | Spur. [30%] |
|-------------|---------------|--------------|-----------|------------------|-------------|-----------|
| GOODS-N 100 | 10' x 15'     | 30           | 1.00      | 291              | 5.5         | 2.3       |
| GOODS-N 160 | 10' x 15'     | 30           | 1.90      | 317              | 11.0        | 7.0       |
| 100+multi   | –             | –            | 2.01      | –                | –           | –         |
| 160+multi   | –             | –            | 2.54      | –                | –           | –         |
| 160+multi+ | –             | –            | 2.74      | –                | –           | –         |
| 100+160+multi+ | –     | –            | 1.87      | –                | –           | –         |
| 100+multi+zspec | – | –          | 1.62      | –                | –           | –         |
| 160+multi+zspec | – | –          | 1.69      | –                | –           | –         |
| 100+160+multi+zspec | – | –          | 1.25      | –                | –           | –         |
| A2218 100   | 4' x 4'       | 13           | 0.84      | 98               | 3.4         | 3.0       |
| A2218 160   | 4' x 4'       | 13           | 1.59      | 94               | 11.8        | 7.6       |
| LH+ 100     | 24' x 24'     | 35           | \( \sim 1.3 \) | \( \sim 7.8 \) | \( \sim 7.0 \) | \( \sim 4.0 \) |
| LH+ 160     | 24' x 24'     | 35           | \( \sim 2.7 \) | \( \sim 7.0 \) | \( \sim 14.5 \) | \( \sim 9.5 \) |
| COSMOS 100  | 85' x 85'     | 182          | \( \sim 2.0 \) | \( \sim 575 \) | \( \sim 9.5 \) | \( \sim 6.3 \) |
| COSMOS 160  | 85' x 85'     | 182          | \( \sim 4.0 \) | \( \sim 4900 \) | \( \sim 20.5 \) | \( \sim 12.0 \) |

**Notes.** (a) The PEP Lockman Hole field is the ROSAT-HRI and XMM field. (b) COSMOS will reach 213 h of integration at full depth.

---

3 Kindly reduced by Kyoungsoo Lee.