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# DOCUMENT

## PACS Spectrometer HPDP: The separated On-source and Off-source cubes

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## Table of Contents

<b>1</b>	<b>INTRODUCTION</b> .....	<b>4</b>
<b>2</b>	<b>DESCRIPTION OF THE HPDP</b> .....	<b>4</b>
<b>2.1</b>	<b>Why produce on-source and off-source cubes?</b> .....	<b>4</b>
<b>2.2</b>	<b>How the HPDPs were created</b> .....	<b>5</b>
2.2.1	Unchopped line-scan observations.....	6
2.2.2	Unchopped range-scan observations.....	6
2.2.3	Chop-nod observations .....	7
2.2.4	The HPDP scripts .....	9
<b>3</b>	<b>THE HPDP PRODUCTS</b> .....	<b>9</b>
<b>3.1</b>	<b>What cubes were produced?</b> .....	<b>9</b>
<b>3.2</b>	<b>How do the HPDP and the SPG products compare?</b> .....	<b>10</b>
<b>3.3</b>	<b>Naming convention</b> .....	<b>10</b>
<b>3.4</b>	<b>Postcards</b> .....	<b>11</b>
<b>3.5</b>	<b>HPDP queries in the HSA</b> .....	<b>12</b>
<b>4</b>	<b>DEALING WITH OFF-SOURCE EMISSION</b> .....	<b>12</b>
<b>5</b>	<b>Glossary</b> .....	<b>13</b>



# 1 INTRODUCTION

*This release note concerns the PACS Spectroscopy Highly Processed Data Products called “On-source/Off-source cubes”.*

For the vast majority of PACS spectroscopy observations processed by the automatic pipelines and provided via the HSA, the science-grade products have been background subtracted: the background as observed at an off-source position has been subtracted from the source+background as observed at the on-source position. For most observations it would therefore be necessary to re-process the data in HIPE to obtain separate on-source and off-source data products. To make it easier for the archive user to be able to inspect on-source and off-source data separately, this processing been done and the resulting cubes provided as the “On-source/Off-source” HPDP. In this release note we explain how these cubes were produced and how they are provided.

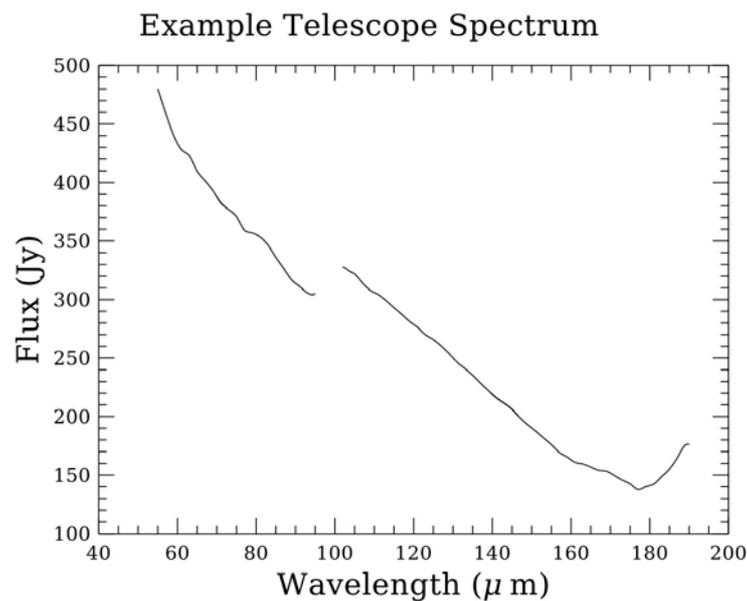
Before reading this release note you should be familiar with PACS spectroscopy, in particular with the various observing modes that were used and different types of cubes that were produced. These are explained in the [Quick-Start Guide](#), and in more detail in the [PACS Products Explained](#) and the [PACS Handbook](#), all of which can be found in the Herschel Explanatory Legacy Library ([PACS](#) section). To follow the advice given in this release note, the user should have at least read the Quick-Start Guide, and should know what observing mode their observation was taken with. Definitions are provided at the end of this release note, but to *understand* the terms defined, it is necessary to read the other documentation.

## 2 DESCRIPTION OF THE HPDP

### 2.1 Why produce on-source and off-source cubes?

The final products produced by the automatic (SPG) pipelines for most PACS spectroscopy observations in the HSA are background subtracted: the <telescope mirror+astronomical background> data as observed from an off-source position has been subtracted from the <telescope mirror+astronomical background+source> data taken at the on-source position. Specifically, the science-grade cubes and spectral tables found at Levels 2 and 3 for the chop-nod observations, at Level 2 for the unchopped line-scan observations, and at Level 2.5 for the on-source unchopped range-scan observations, are background subtracted. The only exception is for the small subset of unchopped range-scan observations for which the observer did *not* request that an off-source position was observed – in which case the final data products are in Level 2.

The “background” for PACS spectroscopy is predominantly that of the telescope’s mirror, certainly in the case of the continuum contribution. An example telescope spectrum is shown in Fig. 1. How well the *astronomical* background was removed by the SPG pipeline depends on how representative the data taken at the off-source position is of the astronomical background at the on-source position; choosing an appropriate off-source position was the responsibility of the observer.



**Figure 1** The telescope spectrum from OD 863. The gap is where data are excluded as they are “out of band”, which is also why the spectrum ends at 190 μm (beyond that lies the “red leak”).

To make it possible for archive users to inspect their observation to check for the presence of spectral features or (to a lesser degree) for extra continuum emission in the off-source data, using any cube visualisation software, separate on-source and off-source cubes were created for each observation using modified versions of pipeline scripts which are available in HIPE. These are provided as the “On-Off” HPDP.

## 2.2 How the HPDPs were created

The spectral range between 55 and 190 μm is included in this HPDP: data in the blue edge (50–55 μm) and the red leak range (190–206 μm) have not been processed.

Note that if the SPG pipeline did not process all the way to Level 2 or 2.5 in either or both cameras, then no HPDP for that camera/observations is provided.



### 2.2.1 Unchopped line-scan observations

In the unchopped line-scan mode, the on-source and off-source data were collected during the same observation as separate observing blocks. The off-source position is a single sky position that was chosen by the observer. For these observations, separate off-source and on-source cubes *are* created by the SPG pipeline at Level 2, however only the on-source *minus* the off-source data are saved to the observation that can be found in the HSA. To create separate on-source and off-source HPDP cubes was therefore a simple matter of running the SPG pipeline script but excluding the off-source subtraction task, which is almost the final task of the pipeline (the only subsequent tasks are to create mosaic cubes).

However, the on-source and off-source HPDP cubes produced in this way still contain the spectrum of the telescope mirror, as this is part of the “background” that is normally subtracted. While this does not affect the usefulness of the cubes for inspecting for *astronomical* emission in the off-source data, it can make it awkward to compare SPG and HPDP cubes to each other: the telescope spectrum is in the 100s of Jy while the sources are usually only 10s of Jy. An additional task to subtract a standard telescope spectrum from the on-source and off-source cubes was therefore added to the end of the HPDP pipeline script. The spectrum was computed by a task (specRespCalToTelescope) that is a standard part of the SPG pipeline for chop-nod observations. The derivation of the telescope spectrum is described in the [PACS Handbook](#) (spectroscopy calibration chapter) and various technical notes in the Herschel Legacy Library ([PACS](#) section level 2).

The filenames of the HPDP cubes link the on-source and off-source cubes to be compared for each observation, and the cube types and spaxel sizes have been forced to be the same.

#### Notes for particular observations

- For obsids 1342265928 and 1342267875, the observers had mistakenly swapped the on- and off-source coordinates; for this HPDP the two have been swapped back.

### 2.2.2 Unchopped range-scan observations

For the unchopped range-scan observing mode, the on-source and off-source data were collected as two (usually consecutive) observations. The off-source position is therefore a single pointing on the sky at a location that was chosen by the observer. In the SPG data obtained from the HSA, in the respective Level 2s one can find the fully-reduced data of each observation. The background subtraction was done by the SPG pipeline with these Level 2 data (specifically with the rebinned cubes), and the results (the residual rebinned cube and the subsequent mosaic cubes and spectrum tables) were placed in the Level 2.5 of the on-source observation. For more detail, see the pipeline chapter in the [PACS Handbook](#).

Therefore, by comparing a Level 2 cube from the on-source observation to the equivalent



cube at Level 2.5 of that observation, you are comparing non-background subtracted data to background-subtracted data. Alternatively, the Level 2 cubes of the off-source observation can be compared to the Level 2 or 2.5 cubes of the on-source observation. To know the obsids of the off-on unchopped range-scan pairs, consult the qualitySummary comments (most easily read from the “QCR” column in the HSA search results panel), or this [list](#) on the HSC Data Products page.

However, to allow for a more direct comparison of the on-source and off-source cubes, it was decided to nonetheless produce HPDP cubes for the unchopped range scans also. The only difference between the HPDP and the SPG pipelines is that the type of cube to create, and its spatial pixel size, was determined by the observing mode of the on-source observation for the HPDP cubes, while the SPG pipeline decided this independently for the on-source and off-source observation (this only makes a difference for mapping observations, where the off source is always a pointed observation and therefore may have different types of cube with different sized spatial pixels to the on-source observation).

As with the unchopped line scans – and for the same reason – the telescope background spectrum has been subtracted from the HPDP cubes.

### Notes for particular observations

- Observations 1342269521 and 1342269523 are on-source observations that share 1342269522 as the off-source observation. In the off-source observation, two wavelength regions (in the red and blue camera each) were requested, one to be used for each of the sole wavelength regions (in each camera) requested for the on-source observations. The HPDP cube FITS filenames are unique in obsid, camera, cube type, and *slice number*, and in this case this would have resulted in the off-source cubes produced for these two on-source observations having exactly the same filename but with different wavelength ranges. To avoid this, the slice numbering was changed and the following files go with each other:
  - hpacs1342269521\_20hps3deqi[br]\_ON\_00 with hpacs1342269522\_20hps3deqi[br]\_OFF\_01
  - hpacs1342269523\_20hps3deqi[br]\_ON\_00 with hpacs1342269522\_20hps3deqi[br]\_OFF\_00
- Observations 1342269518, 20 (on) and 1342269519 (off) have the same situation. The following files go with each other:
  - hpacs1342269518\_20hps3deqi[br]\_ON\_00 with hpacs1342269519\_20hps3deqi[br]\_OFF\_01
  - hpacs1342269520\_20hps3deqi[br]\_ON\_00 with hpacs1342269519\_20hps3deqi[br]\_OFF\_00
- For several other observations the same off-source is used for more than one on-source: however if the order of the wavelength ranges in the related observations is always the same, no change was required to the filenames.

### **2.2.3 Chop-nod observations**

In the chop-nod mode, the on-source and off-source data were collected during the same observation. The two off-source pointings were placed equidistantly either side of the on-



source position. The on-source and off-source positions were taken via a combination of chop-on and chop-off positions taken in telescope nodA and nodB pointings, with a total of 4 permutations. The SPG pipeline subtracts the off-source data-points in the Level 0.5 part of the pipeline. See the [PACS Handbook](#) for more detail.

The HPDP script for chop-nod observations was based on the ‘Split On-Off’ interactive pipeline in HIPE. In this script, the on-source and off-source chop/nod positions are separated at Level 0.5 (rather than subtracted), and the data then processed normally up to Level 2. The end result of the HPDP script is a single on-source cube (the average of the nodA and nodB chop-on positions) and two off-source cubes (the separate nodA and nodB chop-off positions).

As with the unchopped line-scan data, and for the same reason, a telescope background spectrum was subtracted from the on-source and off-source cubes. In the unchopped mode, the same telescope spectrum can be subtracted from the on-source and off-source data since these sky positions have the same line-of-sight through the telescope mirror. For the chop-nod observations, however, the two chopper positions used have a different line-of-sight through the telescope mirror, enough so that the telescope spectrum that forms the main part of the “sky background” is different in the two. This results in an additive offset in the intrinsic telescope background in the nodA and nodB HPDP cubes. Since the nodA and nodB on-source data are averaged together at the end of the pipeline, this does not matter. However, the nodA and nodB off-source data are not; there will therefore always be an additive offset between their spectra. The telescope background subtracted from the nodA and nodB data in the HPDP pipeline is an *average* spectrum, therefore this the additive offset remains. Therefore, if the user wants to compare the off-source continuum level to the on-source continuum level, it will be necessary to also average together the fluxes of the nodA and nodB off-source cubes first.

The flux calibration scheme used in the HPDP script is the so-called “Calibration Block and RSRF” scheme, which is different to “Telescope normalisation” scheme used in the SPG processing for chop-nod observations (but is the same as that used for the unchopped mode observations). The two schemes return similar results when applied to the same data, however note that while some sources of calibration error have the same affect on data produced via the two schemes, not all do. Consequently, when the two schemes are applied to the same data, *differences of up to 15% in the fluxes of the continuum and independently in the integrated fluxes of emission lines can be expected.* The two schemes are explained in the [PACS Handbook](#).

### Notes for particular observations

- For observation 1342254240, three spectral ranges were observed, and subsequently processed by the SPG pipeline. However, for the third range (slice 02: 84.7–86.5  $\mu\text{m}$  in the blue and 169.5–172.5  $\mu\text{m}$  in the red) no nodB off-source position was observed.

The result is an incorrect continuum level in the SPG product and no nodB off-source data. Since this third spectral range is anyway covered by the longer of the two other ranges (for both cameras), it was decided to not provide the HPDP on-source or off-source data for this range.

#### 2.2.4 The HPDP scripts

The scripts used to produce the HPDP cubes are based on the SPG scripts for unchopped observations, and the ‘Split On-Off’ pipeline script for chop-nod observations. The HPDP scripts are provided via the [HPDP legacy repository](#). With minor modifications they can be used to recreate the HPDP cubes in HIPE for any observation. Details of the scripts are given in Table 1.

HPDP_OnOff_chopnod_main.py	Main script for chopnod HPDPs: runs the following three scripts and then writes the products to disc
HPDP_OnOff_chopnod_pipeline.py	Runs the pipeline to create rebinned cubes
HPDP_OnOff_chopnod_telbackSubtract.py	Does the telescope background spectrum subtraction
HPDP_OnOff_chopnod_mosaicCubes.py	Creates the mosaic cubes
HPDP_OnOff_unchoppedLine_main.py	Main script for unchopped line-scan HPDPs: runs the following three scripts and then writes the products to disc
HPDP_OnOff_unchoppedLine_pipeline.py	Runs the pipeline to create rebinned cubes
HPDP_OnOff_unchoppedLine_telbackSubtract.py	Does the telescope background spectrum subtraction
HPDP_OnOff_unchoppedLine_mosaicCubes.py	Creates the mosaic cubes
HPDP_OnOff_unchoppedRange_main.py	Main script for unchopped range-scan HPDPs: runs the following two scripts and then writes the products to disc
HPDP_OnOff_unchoppedLine_decideMappingType.py	Determines what types of mosaic cubes to create
HPDP_OnOff_unchoppedLine_telbackSubtract.py	Does the telescope background spectrum subtraction

Table 1: names and description of the scripts to creating the HPDPs in HIPE

To create a different sort of cube, or to give them different sized spatial pixels, the HPDP scripts can be combined with the relevant lines of code in a PACS useful script in HIPE called ‘Create mosaic cubes with any spaxel size’. To create rebinned instead of mosaic cubes, it is simply necessary to skip the mosaicking tasks.

### 3 THE HPDP PRODUCTS

#### 3.1 What cubes were produced?

Only a single on-source and two (chop-nod) or one (unchopped) off-source cube for each spectral range (for each “slice”, in the terminology of the PACS pipeline) in each observation is provided in these HPDPs, rather than the full range of Level 2/2.5/3 products found in a SPG download. The type of cube provided depends on the observing mode:

- Pointed observations: interpolated cubes with 3” spaxel size
- Mapping observations: cubes with 3” spaxel size, being projected cubes for Nyquist



and oversampled mapping observations, and interpolated cubes for undersampled mapping observations

- Tiling observations: interpolated cubes with 3" spaxel size
- Tiling observations with disjointed pointings (a jump of at least 44" between pointings): projected cubes with 1.5" spaxel size (this was to avoid "stretching" between the disjointed FoVs)

The same cube type with the same sized spatial pixel is provided for the on-source and off-source cubes. The cube types for the red and blue camera data are, however, decided independently and may be different to each other (this was standard practice in the SPG pipeline: for more detail and for the rules determining which cubes were produced for which observing mode/camera combination).

The cubes are the so-called "equidistant" cubes that are also the cube type provided as Standalone Browse Products in the HSA (see the [PACS Products Explained](#) for more detail). The "equidistant" refers to the spectral grid in the cubes, being regular and equidistant, with the WCS containing all necessary details for any software to understand the spatial *and* spectral grid of the cubes. Equidistant cubes are therefore easier for external (non-HIPE) cube-viewing software to understand.

Most of the (un-gzipped) FITS files are a few up to 20Mb in size.

### 3.2 How do the HPDP and the SPG products compare?

As explained above, only the equidistant interpolated or projected cubes are provided in this HPDP. However, many types of PACS spectroscopy products – out of a choice of rebinned cubes, mosaic cubes (interpolated, projected, and drizzled), and two spectrum tables – are provided in an SPG download. This is because different types of product are recommended for science use for different types of observation *and* astronomical source; therefore, almost the entire range of products were created for each observation for the user to be able to choose which ones to use. The product-use recommendations are given in the [Quick-Start Guide](#) and this [product decision tree](#), and the various products themselves are explained in the [PACS Products Explained](#).

The range of products in this HPDP is limited to a few types of cube because their use-case is limited to: load the on-source and off-source cubes into any cube visualisation software, and check for off-source emission. See Sec. 4 for more information about what to do off-source spectral features *are* found.

### 3.3 Naming convention

The cube filenames include the obsid, instrument, cube type, pipeline level, and camera. In addition, the spectral range of each cube – out of the list of observer-requested wavelength



ranges for that observation – is indicated in its filename as a slice number.

The naming convention is the following:

`hpacs<OBSID>_20hps3d<SUFFIX>_<ON|OFF>_<SLICE NO.>.fits`

where:

- `hpacs`: Herschel PACS
- `OBSID`: is the 1342xxxxxx observation identification number. For chop-nod and unchopped line-scan observations, the on-source and off-source data were taken during the same observation and hence have the same obsid. For unchopped range-scan observations the obsid of the on-source and off-source cubes differ because they were taken as separate (usually consecutive) observations. The on-off obsid pairings can be found in this [list](#) provided on the HSC Data Products page. This information can also be found in the FITS keywords `OBSID001` (on-source) and `OBSID002` (off-source) that are in extension 0 of both the on-source and the off-source cubes.
- `20hps3d`: from pipeline Level 2.0, Herschel-PACS-spectroscopy-cube
- `SUFFIX`: indicates the type of cube and the camera:
  - `eqpr|eqpb` is the equidistant projected red or blue cube
  - `eqir|eqib` is the equidistant interpolated red or blue cube
- `ON|OFF`: indicates if this is an on-source or off-source cube; OFFA and OFFB for the chop-nod observations where two different off positions are observed.
- `SLICE NO.`: the different wavelength ranges in any observation are indicated as a “slice” number. The same slice numbers as found in the SPG product are also found here: slice 00 in the HPDP product will be the same wavelength range, for that camera, as slice 00 in the SPG product. The wavelength range of the slice can be found either by opening the cube in an appropriate viewer, or looking for the keywords `MINWAVE` and `MAXWAVE` in the FITS file (extension 0). Alternatively, a [spreadsheet](#) containing all the relevant AOT-related keywords and the wavelength-vs.-slice information can be found on the Herschel Legacy Library ([PACS](#) section level 2).

### 3.4 Postcards

Some examples of postcards are shown in Fig. 2. The postcard is a jpeg file that contains the area-averaged spectrum (flux in Jy/spaxel, where the size of the spaxel is given in the Y-axis label). The obsid is included in the filename. The on-source and off-source data are plotted together. These postcards are provided in the HPDP download, and the “main” postcard for each observation is also displayed in the HSA search results panel. For line-scan observations, the prime and parallel wavelengths are provided as separate postcards with the prime wavelengths making the main postcard. If no prime or parallel range exists in an observation, then clearly that postcard is not provided. For range-scan observations, the prime and parallel ranges are plotted together in a single postcard per on-source observation.



(The ranges that were specifically requested by the observer are the “prime” ranges, and those coming from the other camera are the “parallel” ranges.)

Note that the level of the continuum of the on-source and off-source positions can be quite different. The spectra plotted can sometimes lie at very different fluxes and thus look very “flat” in the postcard. In addition, since the spectra are the average of the entire field, faint lines can be “washed out” in the postcard. It is therefore always worth inspecting the cubes themselves.

### 3.5 HPDP queries in the HSA

The HPDPs are served directly as gzipped FITS files in the HSA interface when inquiring for HPDP. Both on-source and off-source HPDPs are provided when an inquiry is made via the HSA, even if the obsids of the two differ (as is the case for the unchopped range-scan observations). The entirety of this HPDP can also be obtained from the HSA (but it is an extremely large file!). Within this, each obsid is wrapped into a tarfile containing the on-source and off-source cube FITS files and the postcards. For the unchopped range scans, the tarfiles are only provided for the on-source obsids, these containing the off-source obsid data with the on-source obsid data.

## 4 DEALING WITH OFF-SOURCE EMISSION

If emission is found in the off-source cubes, what can the user do? The answer to this depends on what type of emission is present, and whether it is expected (i.e. it *should* be subtracted) or not (the background subtraction needs to be *skipped or modified*). In any case, if there are spectral lines in the off-source data, or significant continuum emission over that produced by the telescope spectrum, then *whether or not* this should be subtracted, skipped, or modified, it may be necessary to run a pipeline script in HIPE to create new Level 2/2.5 products, i.e. the SPG data gotten from the HSA may be incorrect in one way or another. Whether this is necessary or not depends on the significance of the contamination and on the observing mode. A [technical note](#) (‘Dealing with contaminated off-source data’) containing the necessary advice can be found on the HELL pages ([PACS](#) section Level 2). We stress here that there are no scripts provided in HIPE to *correct* for contamination, e.g. to remove emission lines from the off-source data before they are subtracted from the on-source data, but the user can *minimise* the effect of contamination using various scripts in HIPE (and as HIPE is a full scripting environment, they could also chose to manipulate the off-source data themselves before subtracting them from the on-source data).

## 5 Glossary

**Chop-Nod observing mode:** Two ways were provided by PACS to sample the background from an off position. These are explained in the [PACS Handbook](#). The chop-nod mode was the most used because it produced data with a better continuum reliability and slightly better SNR. In this mode the telescope chopped between an on-source and off-source location at two nod positions.

**HSA:** Herschel Science Archive

**HIPE:** Herschel Interactive Processing Environment

**Mapping observing mode:** Two pointing modes were offered for observing with PACS. Mapping observations were performed as a raster of pointings.

**Mosaic cubes (Interpolated, Projected, Drizzled):** Mosaic cubes are those created by combining individual cubes taken in a mapping observation: separate and slightly-offset pointings combined to observe either a larger field or to improve the spatial sampling of the source. Three mosaicking tasks were provided by the pipeline (specInterpolate, specProject, and drizzle). Which one or two of these tasks were run for each observation depended on the observing mode. All mosaicking tasks created new cubes by combining the data of overlapping spaxels of the input cubes to create the data in the spatial pixels of the output mosaic cube. They differ in the algorithm used to do the mosaicking (see the [PACS Handbook](#) for details). Mosaic cubes are also offered for pointed observations, the reason for this was to create cubes with a regular spatial grid which can load more easily into cube-viewing software.

**PacsCubes:** The first cube of the pipeline, from which the rebinned cubes are created.

**Pointed observing mode:** Two pointing modes were offered for observing with PACS. Pointed mode observations were on a single FoV.

**Rebinned cubes:** “Rebinned cubes” are the final fully-calibrated native cubes that are produced by the pipeline: one cube per requested wavelength range and, for mapping observations, per raster position. It is from the rebinned cubes that the mosaic cubes are produced – these mosaic cubes being the end product for most mapping observations and one possible end product for pointed observations. (The rebinned cubes have the 5x5 grid of 9.4”-sized spaxels that is the native sky footprint of the PACS IFU, while the spatial grid of the mosaic cubes depends on the mapping field requested by the observer and the size chosen for the mosaicked spatial pixels.)

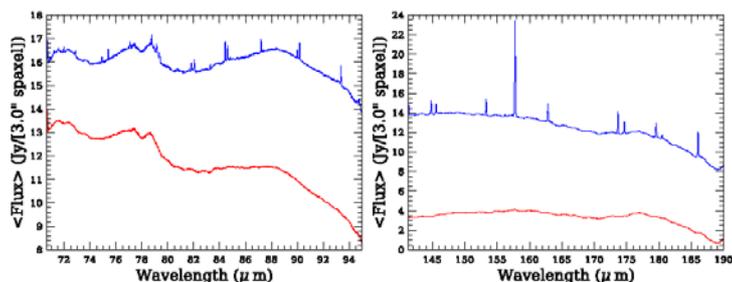
**SPG:** Standard Product Generator, short-hand for the automatic pipeline run at the HSC for all Herschel observations. The SPG download/products are the “pipeline” products that a user downloads from the HSA after an archive search.

**Spatial Pixel/Spaxel:** Both are the name given to the pixels of a cube, each of which contains a full spectrum for a small patch of sky. The difference is that *spaxel* usually refers to the pixel of a native cube (for PACS that is the rebinned cube) with an area that is determined only by the instrument (i.e. 9.4” for PACS); *spatial pixel* refers to the pixel of a mosaic cube, and it can have any size – the ideal size depends on the mosaicking algorithm and the pointing pattern of the observation (how many overlapping spaxels are there in each spatial pixel?).

**Unchopped observing mode:** Two ways were provided by PACS to sample the background from an off position. These are explained in the [PACS Handbook](#). The Unchopped mode was offered for observations of crowded sources where the off-position had to be especially chosen. A block of on-source was followed by a block of off-source observing.

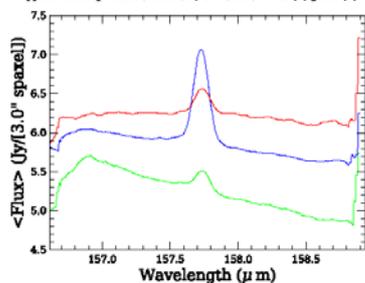
8386252-517116 OnOff Postcard

On: 1342227345 Off: 1342227343  
 PACS Spectroscopy, Unchopped, Range, Pointed.  
 Blue = On source (no background subtraction)  
 Red = Off source (background)



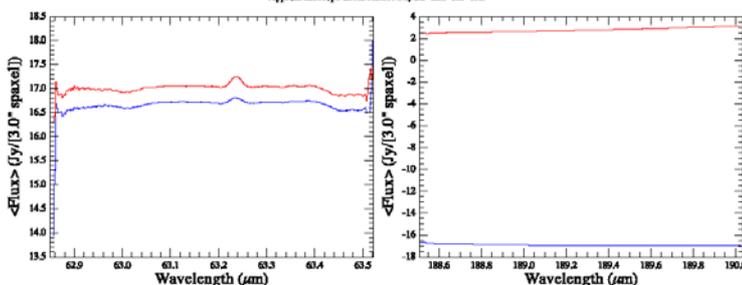
NGC 5315 OnOff HPDP

1342182004 PACS Spectroscopy, Chopped, Line, Pointed.  
 Prime wavelengths:  
 Approx. telescope back. subtracted; On=blue Off=red (A) green (B)



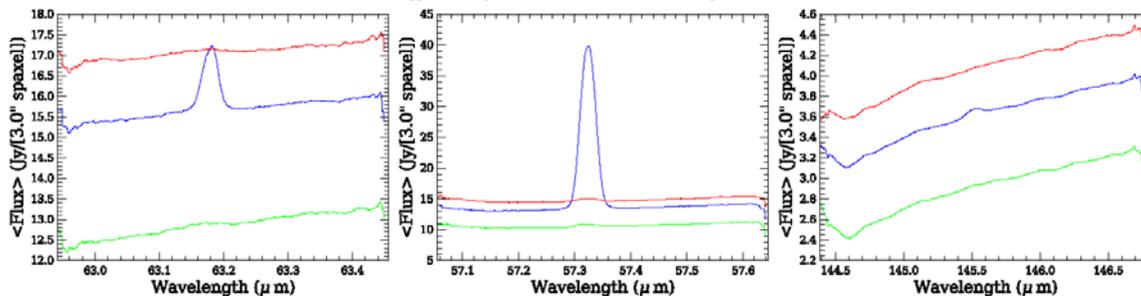
NGC4449\_center\_CIImap-1 OnOff HPDP

1342197814 PACS Spectroscopy, Unchopped, Line, Raster.  
 Prime wavelengths:  
 Approx. telescope back. subtracted; On=blue Off=red



NGC6543 OnOff HPDP

1342213681 PACS Spectroscopy, Chopped, Line, Pointed.  
 Prime wavelengths:  
 Approx. telescope back. subtracted; On=blue Off=red (A) green (B)



52 Europa OnOff HPDP

1342270773 PACS Spectroscopy, Chopped, Range, Pointed.  
 Approx. telescope back. subtracted; On=blue Off=red (A) green (B)

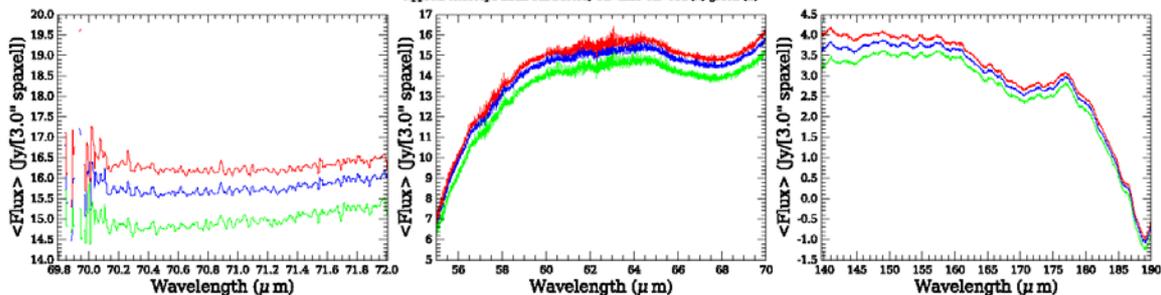


Figure 2: OnOff postcards. The blue spectrum is from the on-source data, the red curve (for unchopped observations) and red and green curves (for chop-nod observations) is/are from the off-source data.