The Hershel PN Survey, HerPlaNS: Spectroscopy

K.M Exter[1], D. Ladjal[2], T. Ueta[2,3], M. Otsuka[4], R. Szczerba[5], N. Siódmiak[5], I. Aleman[6], J.H. Kastner[7], R. Montez[8], I. McDonald[9], M. Wittkowski[10], S. Ramsted[11], O. De Marco[12], E. Villaver[13], B. Balick[14], E.G. Blackman[16], Y.- H. Chu[17], K. Hebden[9], J.L Hora[18], H. Izumiura[19], J.A. Lopez[20], K. Murakawa[21], J. Nordhaus[22], R. Nordon[23], C. Sandin[23], R. Sahai[24], A.G.G.M. Tielens[6], P.A.M. Van Hoof[25], W. Vlemmings[26], I. Yamamura[3], A. Zijlstra[9]

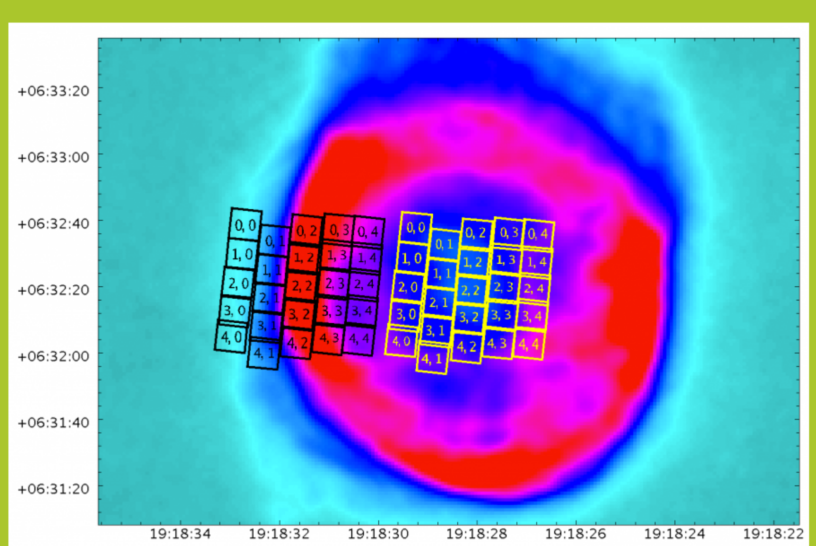
1 IVS, KU Leuven, Belgium
2 Univ. of Denver, CO, USA
3 ISAS/JAXA, Tokyo, Japan
4 ASIAA, Taipei, Taiwan
5 NCAC, Warsaw, Poland
6 Leiden Univ., Netherlands
7 RIT, Rochester NY, USA
8 Vanderbilt Univ., TN, USA
9 Univ. of Rochester, NY, USA
10 ESO, Garching, Germany
11 Uppsala Univ., Sweden
12 Macquarie Univ., Sydney, Australia
13 UAM, Madrid, Spain
14 Univ. of Washington, WA, USA
15 Technion, Haifa, Israel
16 Univ. of Rochester
17 Univ. of Illinois, IL, USA
18 CfA, MA, USA
19 OAO/NAOJ, Japan
20 UNAM, Mexico City, Mexico
21 Leeds Univ., UK
22 MPE, Garching, Germany
23 IAP, Postdam, Germany
24 JPL Caltech, CA, USA
25 ROB, Brussels, Belgium
26 Chalmers/OSO, Sweden

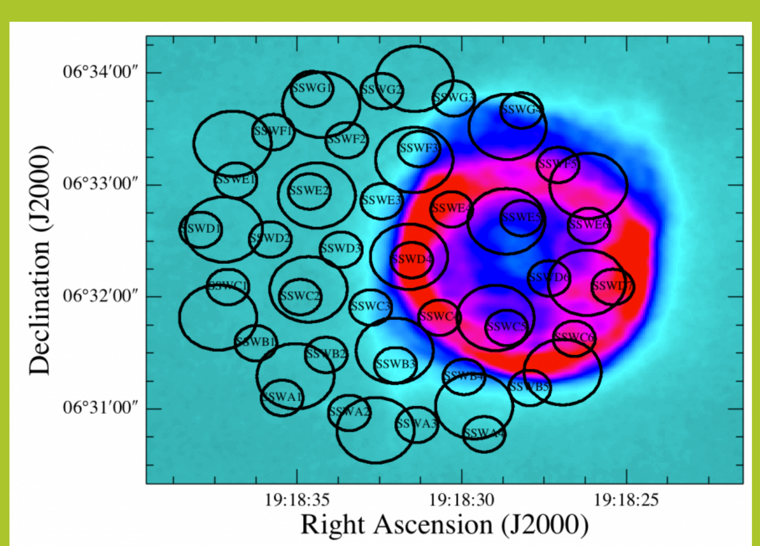
1. HerPlaNS

The Herschel Planetary Nebula Survey HerPlaNS is a ~200 hour Herschel programme dedicated to the investigation of 11 PNe. We aim to study the spatial distribution and chemical composition of the cold dust and gas components via far-IR imaging and spectroscopy, and to investigate the energetics of the gas-dust systems as function of location in the nebula using spatially resolved spectroscopy data.
HerPlaNS makes use of the full observing capabilities of the PACS and SPIRE instruments. The observations consist of:
- Photometry maps covering the full extent of the planetary nebulae at: 70μm, 160μm, 250μm, 350μm and 500μm.
- Spectroscopy from 70μm to 672μm, at one to two locations in the PNe.
- PACS spectral line maps at higher resolution for two PNe around 8 emission lines: [OIII] 52μm, [NIII] 57μm, [OI] 63μm, [OIII] 88μm, [NII] 122μm, [OI] 146μm, [CII] 157μm and [NII] 205μm.

2. The spectroscopy observations

PACS is an integral field unit, consisting of a 5x5 spaxel box covering an area of 47"x47". Each PACS pointing therefore produces spectra from 25 nigh-contiguous regions, over a wavelength range ~50-210μm. The spectra can be combined spectrally or spatially to create region-spectra or integrated flux maps.
SPIRE is an FTS spectrometer and each single pointing covers a (unvignetted) diameter of 2' with 35 (194-313μm) or 19 (303-672μm) separate detectors. The spectra are less easy to integrate spatially because the circles of the bolometers not fully contiguous but, as we will show, you can still use the spectra to investigate spatial variations in the spectra of the PNe.

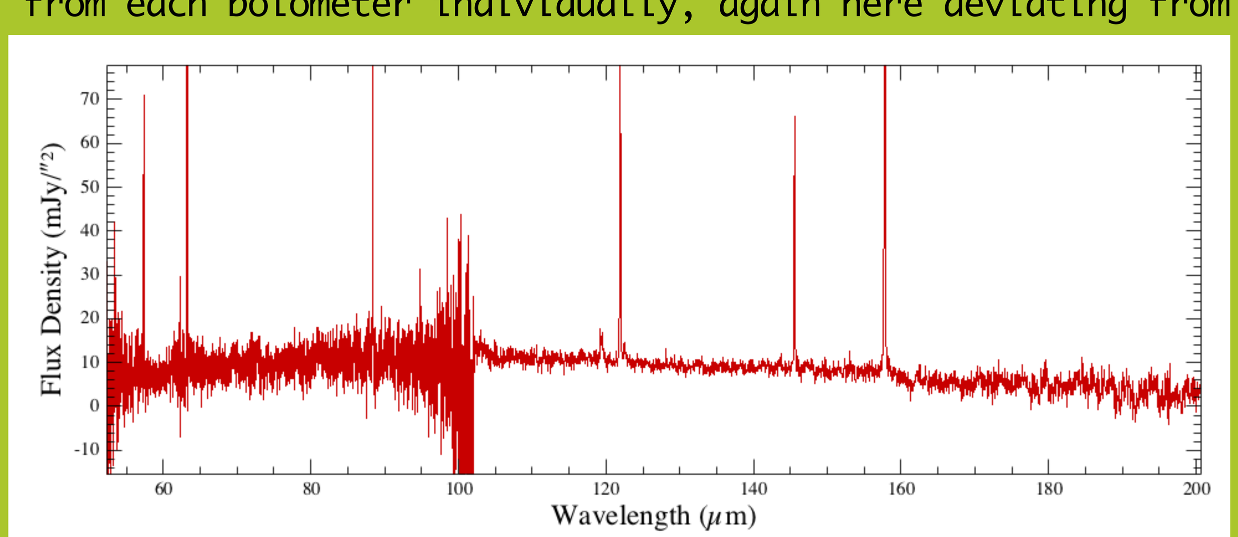




The footprints of the HerPlaNS pointings on NGC 6781: left PACS (both fields) and right SPIRE (one field shown). The footprints of the two instruments differ because of the different instrument designs, in particular because the beam size increases with wavelength (PACS spectra are to the blue of SPIRE). (Note: the SPIRE circles are drawn smaller than they actually are: the short (smaller) and long (larger) wavelength bolometer circles do touch at their edges.)

3. The data reduction

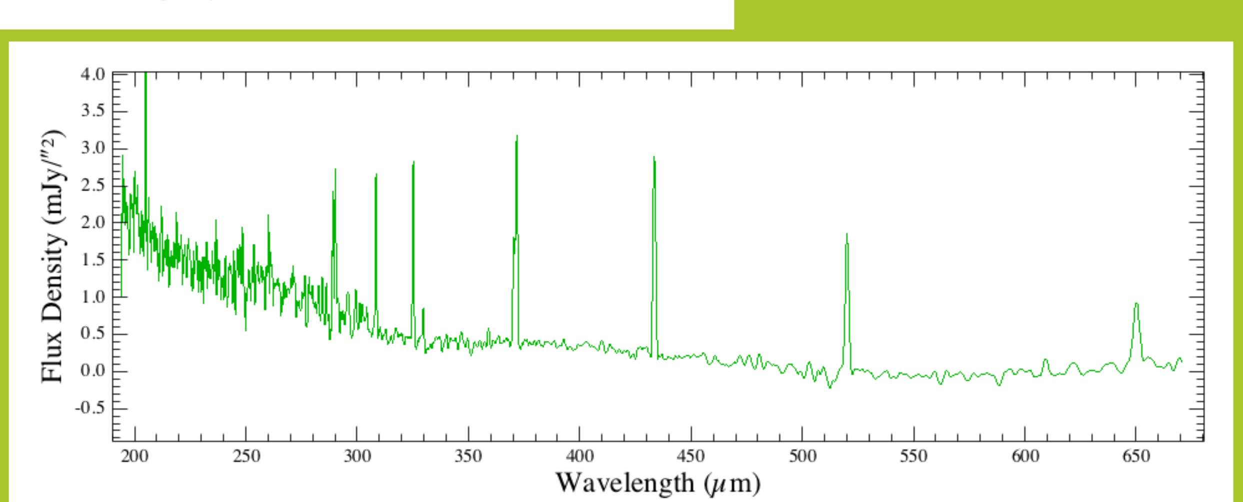
Our data reduction strategy in general followed the recommendations of the respective data reduction guides.
For PACS the main decision point is which pipeline to use, there being different flux calibration and (telescope) background subtraction methods. We chose the "background normalisation" method which uses the telescope background (observed as the off-chops in the chop-nod observing method) to both subtract the background and flux calibrate the data. The resulting spectra match very well at the band edges, show clear emission lines, and even faint continuum levels are satisfactorily detected.
For SPIRE the main decision point is the background subtraction, which affects the SNR of the resulting spectra as well as their reliability. We used our own dedicated sky observations for this, resulting in cleaner spectra with better SNR than the standard pipeline provides. We also extracted and reduced the spectrum from each bolometer individually, again here deviating from the standard pipeline.



PACS and SPIRE spectra of NGC 6781, taken from the western rim pointing.

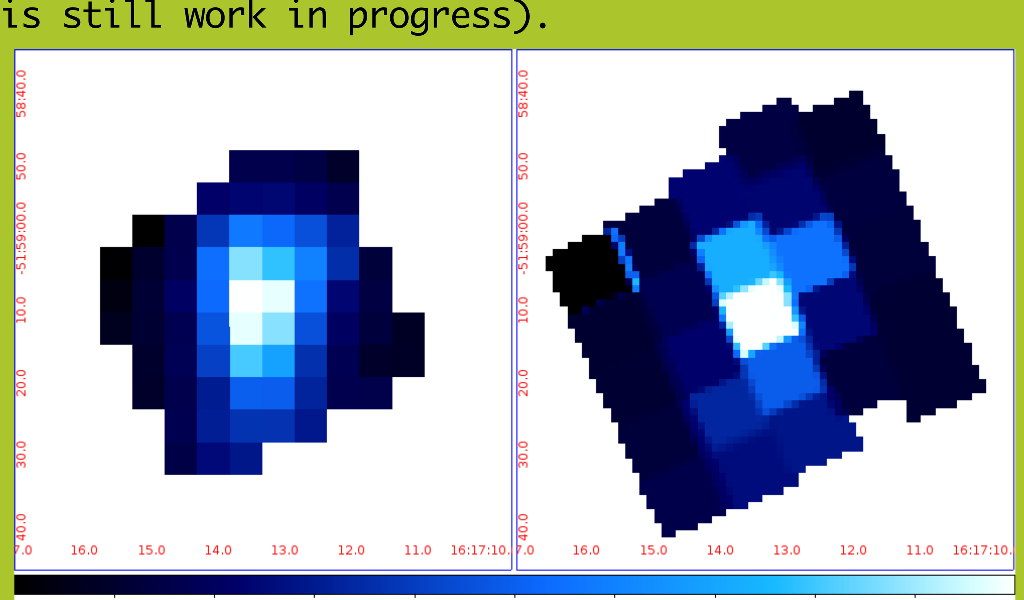
Left: from the central spaxel (PACS). Lines of [O I,III], [N II,III], and [C II] are present.

Below: from the central bolometer (SPIRE). Most lines here are CO.



4. Making spectral maps from PACS

This section provides a bit of technical information about making line maps from PACS spectroscopy. Images can be created from fitted emission line integrated fluxes. First measure the emission lines in each spaxel. Then create a regular spatial grid from the slightly irregular sky footprint that PACS has (see figure above), and resample the fluxes from the original grid to the new regular one.
However, with single pointing (i.e. not mapping) observations, there is the problem that as the spaxels are only a bit smaller than the beam, you are spatially undersampling the beam. This always creates problems when regridding data. PACS offers two ways to do this for such observations: (i) "project" the fitted values from their original grid to a grid of small spaxels (1 arcsec), (ii) create a new spatial grid with any pixel size using Delaunay triangulation and simple interpolation of the fluxes to the new grid.
In HerPlaNS we are still deciding which method is better. The Delaunay traingulation+interpolation is better for creating mosaics from several separate pointings, and projection is generally *only* recommended when you have spatially *over*sampled the beam. But the advantage of using the projection with *small* pixels is that you can still see the original footprint and hence do not create any spatial artifacts that can otherwise be created when you project spatially-undersampled data. An example of these two method is shown below (noting that is is still work in progress).



Maps made from the integrated flux in the [OI] emission line at 63.2μm.

Left: using Delaunay triangulation to a regular grid with pixels of 4.5".

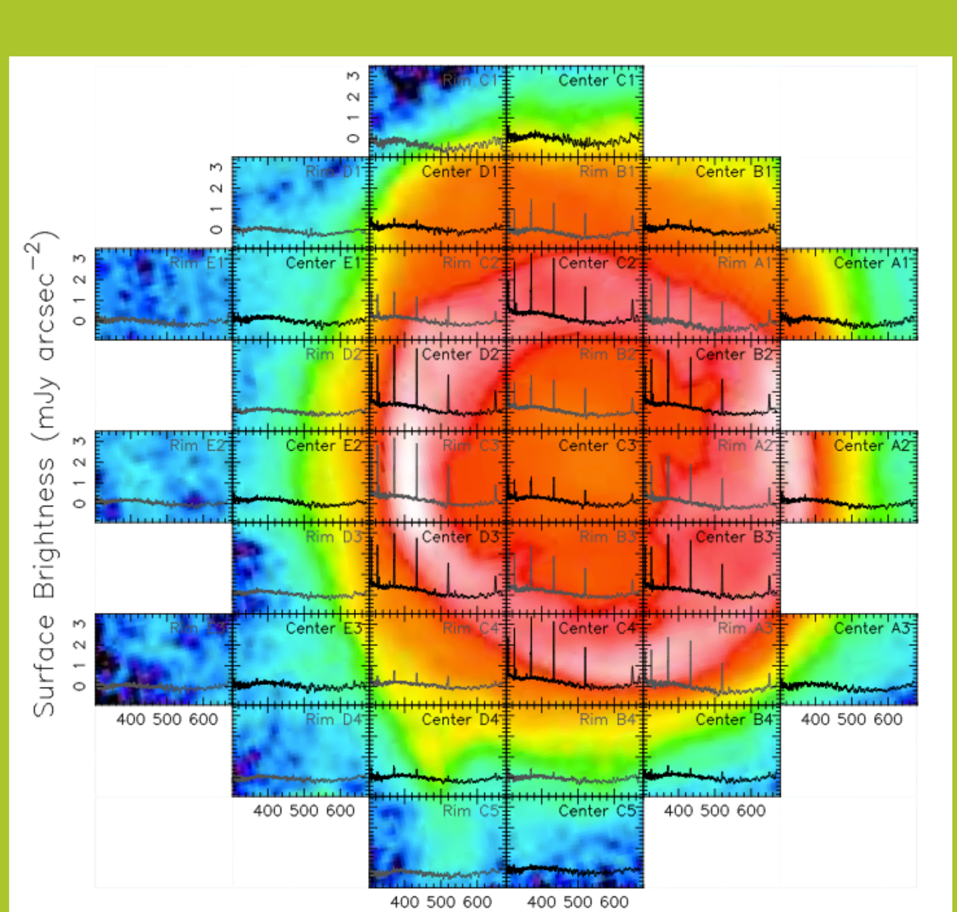
Right: the same data projected with pixels of 1". The 9.4" native pixel size of PACS is easy to see in this image.

Note: the edges of WCS are not exactly the same for the two maps, hence the left map has a smaller extent than the right map. The orientation is the same.

TO BEAR IN MIND: As the PACS beam is larger than the 9.4" native spaxel size (the beam varies from 9" to 14" over the wavelength range), each spaxel actually includes a contribution from all neighboring spaxels. Also, as the beam is larger in the red than the blue, when comparing line maps at different wavelengths it is necessary to convolve the shorter wavelength maps to the beam of the longer wavelength maps.

5. Studying spatial variations from SPIRE data

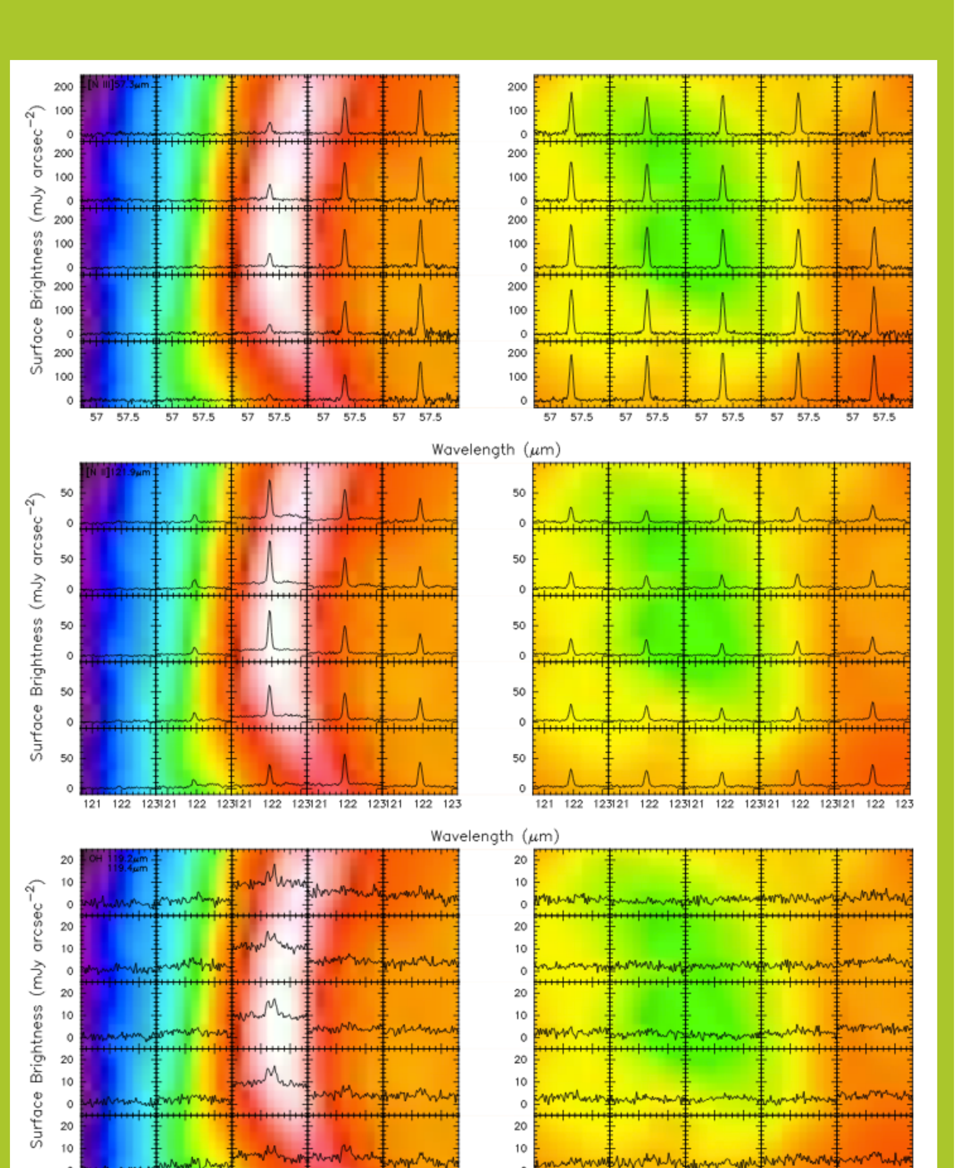
Since for SPIRE spectra is more difficult to make integrated spectral maps, so far we have limited ourselves to plotting the spectra on top of the Herschel images of our PNe. (It should be possible to use the Delaunay triangulation and interpolation scheme used by PACS, and this will be attempted in the future.) Using NGC 6781 as an example again, to the right we show a pseudo-mosaic SPIRE spectral map constructed from the spectra from the SSW/SLW bolometers plotted on top of the PACS 70μm image. A mix of rim (grey) and centre (black) pointing spectra are included. The strong lines you see are all CO. It is clear that the strength of the lines vary between the rim and the centre of the PN.



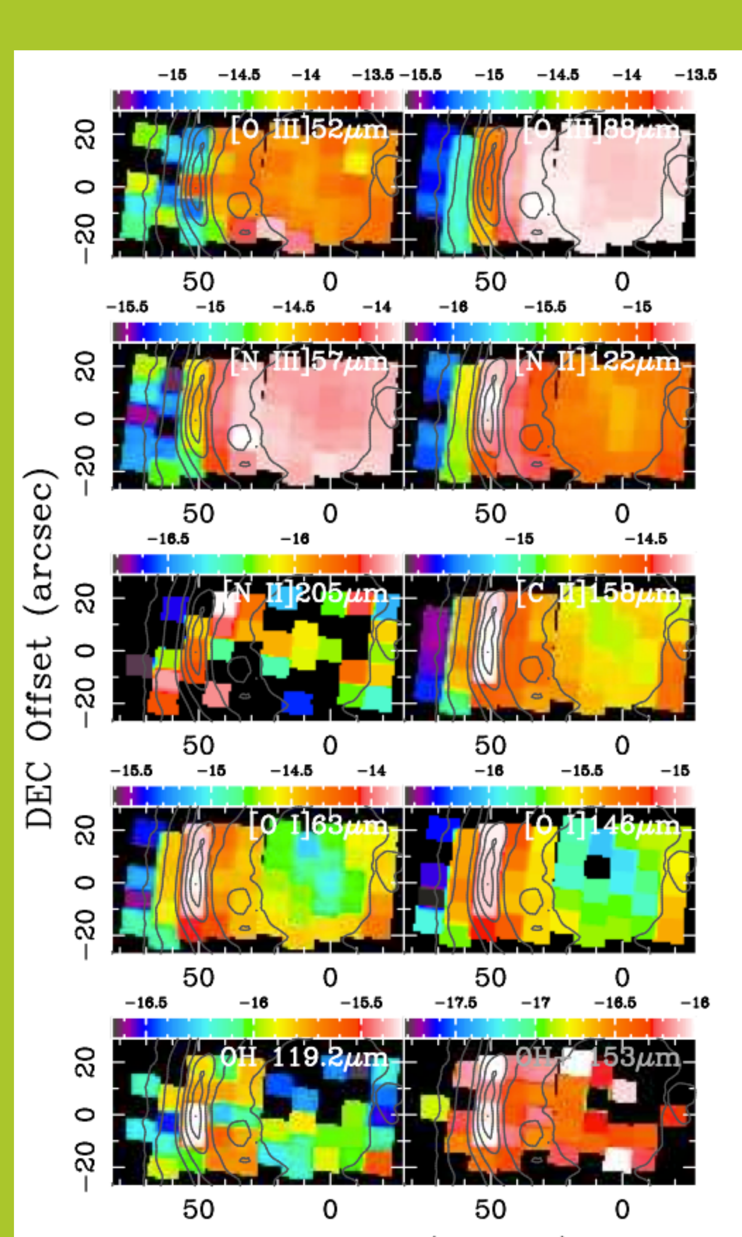
6. The fullest scientific return: compare photometry to spectroscopy

For the best scientific return (and for the prettiest images) we compare the spectral line variations with the Herschel images of our PNe. The broad-band emission arises from the dust in the nebulae (with a small contribution from line emission) and the spectra, of forbidden lines from e.g. O, C, and N and molecules of e.g. OH, CO, arise from the gas. The relationship between these two components can be studied best by comparing their respective spatial distributions. In this way we can also measure variations to the temperatures, densities, and abundances of the different components over the nebula. To the right we show some ways of comparing the PACS spectra to images, for NGC 6781.

For more information on the HerPlaNS project, three papers will shortly be published: an overview by Ueta et al., a report on a first detection of OH+ by Aleman et al., and a comprehensive paper on the photometry by Djazia et al. A spectroscopy paper will follow thereafter. Katrina Exter, Djazia Ladjal, and Toshiya Ueta will also be happy to answer any questions you may have.



Spatially-varying line emission of NGC 6781 at [N III] 57.3μm, [N II] 121.9μm, and the OH doublet 119.2/119.4μm, overlaid with the PACS 70 μm image, indicating locations from which these lines arise. For this PN we find that ionic lines tend to be strong in the highly ionised cavity of the cylindrical structure of this PN (plots on the right), while atomic and molecular lines tend to be pronounced in the cylindrical rim of the nebula (plots on the left).



Integrated line intensity maps. Blank pixels indicate no significant detection. Overlaid are the contours of the PACS 70μm image. The wedges show the log of the line intensity in units of erg/s/cm^2/arcsec^2. You can see that the higher ionisation states peak in the centre of the nebula and the lower ionisation states peak in the rim, where the dust continuum (the 70μm contours) is also brightest.