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A Continuing Challenge through Cosmic Time
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Herschel Planetary Nebula Survey Plus (HerPlaNS+)

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Abstract. We present the current status update of the Herschel Planetary Nebula Survey Plus project (HerPlaNS+) based on the original General Observer HerPlaNS survey program during the OT1 cycle and the follow-up exhaustive archival search of PN observations using the PACS and SPIRE instruments on-board the Herschel Space Observatory.

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1. HerPlaNS

The original Herschel Planetary Nebula Survey (HerPlaNS) was performed using all available observational modes of the PACS and SPIRE instruments aboard Herschel to investigate the far-IR characteristics of both the dust and gas components of the circumstellar nebulae for a set of 11 high-excitation PNe (Ueta *et al.* 2014). We obtained (1) broadband maps of the target sources at five far-IR bands, 70, 160, 250, 350, and 500 μm, with rms sensitivities of 0.01–0.1 mJy arcsec^{-2} (0.4–4 MJy sr^{-1}); (2) 5×5 IFU spectral cubes of 51–220 μm covering roughly a $50'' \times 50''$ field at multiple positions in the target sources, with rms sensitivities of 0.1–1 mJy arcsec^{-2} (4–40 MJy sr^{-1}) per wavelength bin; and (3) a sparsely sampled spectral array of 194–672 μm covering roughly a $3'$ field at multiple positions in the target sources, with rms sensitivities of 0.001–0.1 mJy arcsec^{-2} (0.04–4 MJy sr^{-1}) per wavelength bin.

A quick demonstration of the intended analyses using NGC 6781 as an example yielded the following: (1) the spectral fitting of the broadband images indicated that dust grains are composed mostly of amorphous-carbon based material (i.e., the power-law emissivity index of $\beta \approx 1$) of the temperature between 26 and 40 K; (2) the spatially-resolved plasma diagnostics using line ratios such as [O III] 52/88 μm and [N II] 122/205 μm resulted in the electron density and temperature (n_e, T_e) and ionic/elemental/relative abundance profiles exhibiting variations along the radial direction in the equatorial plane of this nearly pole-on bipolar nebula; and (3) the direct comparison between the above results allowed us to derive an empirical gas-to-dust mass ratio distribution projected roughly to the equatorial plane of this nebula, showing variation of the ratio from 550 at the inner edge of the nebula waist to 100 at the detected outer edge with the average ratio being 195 ± 110.

This demonstration signified the importance of direct and purely empirical comparison between the gas and dust components with PNe, especially in a spatially-resolved manner, to account for the amount of matter and energetics in these nebulae.

2. Detection of OH^+ and H I Laser Emission from PNe

Probing PNe in the less explored far-IR wavelength range allowed us to detect various exotic emission. First, we made the first detections of OH^+ in PNe (Aleman *et al.* 2014). The emission was detected in both PACS and SPIRE far-IR spectra of three of the 11 HerPlaNS PN sample (NGC 6445, 6720, and 6781), with the simultaneous and independent discovery in two other PNe (NGC 6853 and 7293) reported by Etxaluze *et al.* (2014). All five OH^+ PNe are molecule rich, with ring-like or torus-like structures and hot central stars ($T_{eff} > 100\,000$ K). The OH^+ emission is most likely due to excitation in a photo-dissociation region (PDR). Although other factors such as high density and low C/O ratio may also play a role in the enhancement of the OH^+ emission, the fact that we do not detect OH^+ in objects with $T_{eff} < 100\,000$ K suggests that the hardness of the ionizing central star spectra (i.e. the production of soft X-rays, at around 100–300 eV) could be an important factor in the production of OH^+ emission in PNe.

We then reported the detection of hydrogen recombination laser (HRL) lines in the far-IR to sub-mm spectrum of Mz 3 observed as part of HerPlaNS (Aleman *et al.* 2018). Comparison of optical to sub-mm HRL lines to theoretical calculations indicated that there was an enhancement in the far-IR to sub-mm HRLs. The likely explanation for this enhancement is the occurrence of a laser effect, and indicated was the presence of a dense and ionized gas ($n_H > 10^8$ cm^{-3}) in the core of Mz 3, while the empirical analysis of forbidden lines suggested densities around 4 500 cm^{-3} in the surrounding lobes.

3. Comprehensive Panchromatic Data Analyses and Photoionization Modeling of NGC 6781

By augmenting the HerPLANS data with existing data from UV to radio, we performed one of the most thorough plasma diagnostics and ionic/elemental abundance analyses and constructed one of the most comprehensive dusty photo-ionization models ever produced for NGC 6781 (Otsuka *et al.* 2017), which is separately presented in this volume.

4. HerPlaNS+

Presently, we are compiling and analyzing all PACS and SPIRE data obtained for PNe found in the Herschel Science Archive as the expanded HerPlaNS+ survey. More than 1 000 PNe were observed in the photometry-mapping mode and a few dozens in the spectroscopy mode. These results will be published as the subsequent installments of the HerPlaNS series (Ueta *et al. in prep.*).

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