The dusty side of planetary nebulae: a HerPlaNS view

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Abstract. HerPlaNS (Herschel Planetary Nebula Survey) is a far-IR imaging/spectroscopic survey of planetary nebulae (PNe) using the Herschel Space Observatory. In this presentation, we review our investigation into the physical properties of the cold dust component of the target PNe. We find that the far-IR surface brightness emission from PNe is generally dominated by thermal dust emission, which exhibits particular characteristics in terms of the dust emissivity and dust temperature compared with dust grains found elsewhere. The PN dust displays little variation in the emissivity while a large spread in the temperature, suggesting the presence of rather homogeneous dust chemistry and size distribution in the circumstellar environs.

1. The HerPlaNS Survey

The planetary nebula (PN) phase marks the last throes of stellar evolution for stars of about 0.8–8 M☉ initial mass [1]. These stars develop the circumstellar shell of gas and dust via mass loss in the asymptotic giant branch (AGB) and post-AGB phases. During the PN phase, the circumstellar shell undergoes a dramatic transformation (i.e., ionization, photo-dissociation, and dynamical shaping) caused by the fast wind and the intense radiation from the central star and by the less powerful, but often significant interstellar radiation field from the interstellar space. As a consequence, a variety of physical conditions are showcased within PNe, from fully ionized hot plasma to dusty cold atomic/molecular clouds, which exist in a (at least to first order) stratified manner around the central star. Therefore, PNe provide excellent astrophysical laboratories to test theories of stellar evolution and gas-dust dynamical processes in interacting stellar winds that can also interact with the surrounding interstellar medium (ISM).

We conducted a comprehensive far-IR imaging and spectroscopic mini-survey of PNe with the Herschel Space Observatory (Herschel; [2]), dubbed the Herschel Planetary Nebula Survey (HerPlaNS; [3]). Nearly 200 hours of observing time was used to take advantage of Herschel’s mapping capabilities – broadband and spectral imaging as well as spatio-spectroscopy – at high spatial resolutions made possible by its 3.5 m primary mirror. Our chief objective was to examine both the dust and gas components of the 11 target PNe in the far-IR and investigate the energetics of these gas-dust systems in a spatially-resolved manner. In this contribution, we briefly summarize the HerPlaNS survey by focusing on the dusty side of the target PNe.

¹ The HerPlaNS sample consists of NGC 40, 2392, 3242, 6445, 6543, 6720, 6781, 6826, 7009, and 7026, plus Mz3.
2. Broadband Mapping

Far-IR broadband images of the target PNe (covering at most $7' \times 7'$) were taken at 70, 100, and 160 $\mu$m with PACS [4] and at 250, 350, and 500 $\mu$m with SPIRE [5]. Dust emission distribution in the far-IR in these PNe is generally consistent with that of ionized gas line emission in the optical. However, dust emission is generally more extended than ionized gas emission, indicating that the colder dusty molecular/atomic part of the circumstellar shell goes well beyond the “PN proper” region of hot ionized plasma.

The total far-IR fluxes ($F_\nu$) were computed by aperture photometry with the 3-$\sigma_{\text{sky}}$ contour in the 70 $\mu$m map, yielding uncertainties up to 5% for the PACS bands and 15% for the SPIRE bands after color-correction: the resulting spectral energy distributions (SEDs) are shown in Figure 1 (open triangles and asterisks), together with fluxes derived from WISE and Spitzer/IRAC observations (open stars). As seen in Figure 1, the Herschel bands cover the Rayleigh-Jeans shoulder of the thermal dust emission component and often the thermal dust emission peak. Therefore, the dust temperature, $T_{\text{dust}}$, can be estimated by fitting the far-IR SED with a power-law dust emissivity, $\lambda^{-\beta}B_\nu(T_{\text{dust}})$, where $\beta$ defines the emissivity characteristics of dust grains at the temperature $T_{\text{dust}}$. We note here that these measured broadband fluxes would include some contribution from far-IR emission lines. Thus, we assessed the degree of line contamination by using PACS spectra. We found that the level of line contamination was generally minor (median 4% and 2% at 70 and 160 $\mu$m, respectively and insignificant in other bands), while as high as 10–20% for PNe having a hot (> 100K) central star, and hence, line contamination can be safely ignored in the dust emissivity fitting.

![Figure 1](image_url)

**Figure 1.** Thermal dust emission SEDs of the HerPlaNS target PNe

The derived $T_{\text{dust}}$ varies from 38 K (NGC6781) to more than 100 K (NGC3242 and 6826). When the dust SED peak is well constrained within the Herschel bands, the uncertainty of $T_{\text{dust}}$ is less than 10%. However, the uncertainty reaches 30% or more if $T_{\text{dust}} > 65$ K (i.e., the dust SED peaks at < 70 $\mu$m). Overall, there is no single $T_{\text{dust}}$ that fits both the far-IR region...
(the Rayleigh-Jeans side) and mid-IR region (the Wien side) of the observed PN thermal dust emission. Hence, there exist distinct $T_{\text{dust}}$ regimes over these PNe. This is consistent with the fact that the dust distribution in PNe is spread over well beyond the ionized gas region into the atomic/molecular gas regions. These SEDs also indicate that a significant amount of thermal dust emission arises in the far-IR and that a significant amount of cold dust exists in the outer regions of PNe beyond the central ionized region.

The emissivity power index $\beta$ for all PNe we investigated turned out to be 1.1 or less except for NGC 6543 (1.7 ± 0.1). Typically, the value of $\beta$ is roughly 2 for silicate dust grains and graphite grains and close to 1 for amorphous carbon grains (e.g., [6, 7, 8, 9] for theoretical/lab studies).

To investigate the variation of $\beta$ in relation of $T_{\text{dust}}$ within the PN volume for our sample, the derived values of $T_{\text{dust}}$ and $\beta$ at specific spatial locations within the target PNe are plotted (Figure 2). To compare the $\beta$–$T_{\text{dust}}$ relationship in PNe and some other object types (ISM and star forming regions), similarly measured $\beta$ and $T_{\text{dust}}$ values from other objects are also shown in the same plot. The distribution of the $\beta$–$T_{\text{dust}}$ points in the plot appears to show anti-correlation between the two parameters: there is a tendency that the points cluster around a very low $T_{\text{dust}}$ value ($\sim 27$ K) with high $\beta$ values (between 0.1 and 3) and around a low $\beta$ value ($\sim 0.85$) with high $T_{\text{dust}}$ values (between 25 and 88 K). In general, most PN points are found in the low-$T_{\text{dust}}$ and high-$\beta$ part of the distribution: NGC 7009 is the case in which a large spread of values is seen in both $T_{\text{dust}}$ and $\beta$. From the spatial distribution of these points, we see that the high-$T_{\text{dust}}$ and low-$\beta$ points are found close to the PN central stars, while low-$T_{\text{dust}}$ and high-$\beta$ points are found away from the PN central stars. On the other hand, dust in the ISM (starless dark cloud cores) is found at low $T_{\text{dust}}$ with a range of $\beta$ (from 0.5 to 1.4).

![Figure 2](image.png)

**Figure 2.** Spatially-resolved distributions of the dust temperature $T_{\text{dust}}$ and emissivity index $\beta$ in the target PNe and other astronomical objects (W Hya: O-rich AGB, KHA 118 and ISOSSJ18364−0221: starless dark cloud cores, PNG001.8+00.8: bulge PN).

From this result, we can conclude that (1) dust in the inner regions of the circumstellar shell tends to show low-$\beta$ and high-$T_{\text{dust}}$ characteristics and higher-$\beta$, (2) lower-$T_{\text{dust}}$ dust is found toward the outer regions in the circumstellar shell, and (3) lowest-$T_{\text{dust}}$ dust is eventually found in the ISM.

Dupac et al. [10] found a strong anti-correlation between $\beta$ and $T_{\text{dust}}$ using balloon-borne sub-mm observations of different ISM regions with $10 \, \text{K} \geq T_{\text{dust}} \geq 80 \, \text{K}$ and $0.8 \leq \beta \leq 2.4$. Paradis
et al. [11] and Anderson et al. [12] both investigated the $\beta$-$T_{\text{dust}}$ distribution of star forming regions using Herschel data and found an anti-correlation for a smaller range of $T_{\text{dust}}$ and $\beta$. This trending can be explained by the presence of different temperature components along the line of sight and/or a change in dust chemistry or crystallinity, as corroborated by laboratory analysis (e.g. [13, 14, 15]). On the other hand, some authors claim that the observed anti-correlation is caused by incorrect treatment of noise with the least-square minimization fitting (which assumes that $T_{\text{dust}}$ and $\beta$ are independent, but they are not really independent; e.g. [16, 17]). While we are presently investigating the $T_{\text{dust}}$-$\beta$ dependence and its effects in the analysis, we tentatively consider the observed trending is real and represents the change of the physical properties of the far-IR emitting dust (interstellar type vs. circumstellar type) because our finding is found from high signal-to-noise data (i.e., bright regions of PNe) and is still consistent with the previous ISM results.

3. Summary
We conducted a far-IR imaging/spectroscopic survey of PNe using the Herschel Space Observatory. Far-IR broadband imaging probed the dust component of the target PNe at the highest spatial resolution ever used to image these objects, while far-IR spectroscopy permitted detection of ionized, atomic, and molecular line emission from the gas component. Here, we summarized the results of a far-IR broadband imaging mini-survey of 11 PNe [18].

Cold thermal dust emission in the far-IR (50–500 $\mu$m) detected from about a dozen PNe observed as part of the Herschel Planetary Nebula Survey revealed that

(i) in these PNe the largest fraction of thermal dust emission arises in the far-IR part of the spectrum, indicating that the coldest dust component in PNe representing dust grains ejected as part of ancient AGB winds cannot be ignored in accounting for the total mass and energetics, and

(ii) by fitting far-IR broadband fluxes with a power-law dust emissivity, $\lambda^{-\beta}B_\lambda(T_{\text{dust}})$, the spatially-resolved $\beta$-$T_{\text{dust}}$ relationship can separate the circumstellar (with high $T_{\text{dust}}$ and low, specific $\beta$) and interstellar (with low, specific $T_{\text{dust}}$ and high $\beta$) dust components.

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