24μm Excesses of Hot WDs - Evidence of Dust Disks?

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Abstract. Spitzer Space Telescope observations of the Helix Nebula's hot ($T_{\text{eff}} \approx 110 000$ K) central star revealed mid-IR excess emission consistent with a continuum emission from a dust disk located at 35–150 AU from the central white dwarf (WD), and the dust is most likely produced by collisions among Kuiper Belt-like objects (Su et al. 2007). To determine how common such dust disks are, we have carried out a Spitzer 24 μm survey of 72 hot WDs, and detected at least 7 WDs that exhibit clear IR excess, all of them still surrounded by planetary nebulae (PNe). Inspired by the prevalence of PN environment for hot WDs showing IR excesses, we have surveyed the Spitzer archive for more central stars of PN (CSPNs) with IR excesses; the search yields four cases in which CSPNs show excesses in 3.6–8.0 μm, and one additional case of 24 μm excess. We present the results of these two searches for dust-disk candidates, and discuss scenarios other than KBO collisions that need to be considered in explaining the observed near and/or mid-IR excess emission. These scenarios include unresolved companions, binary post-AGB evolution, and unresolved compact nebulousity. We describe planned follow-up observations aiming to help us distinguish between different origins of observed IR excesses.

1. Dust Disk around the Central Star of the Helix Nebula
The central star of the Helix Nebula is a hot white dwarf (WD) with an effective temperature of $\sim 100\,000$ K. Its Spitzer Space Telescope observations have revealed a new phenomenon. While the IRAC 3.6, 4.5 and 5.8 μm observations show a point source well accounted for by the photospheric emission from the hot WD, the 8 μm flux is twice the value expected from a single WD, and the MIPS 24 and 70 μm observations also show a compact source coincident with the WD. A follow-up Infra-Red Spectrograph (IRS) observation of the central point source has confirmed that the mid-IR emission originates from a dust continuum. The spectral energy distribution (SED) of the IR emitter indicates a temperature of 90–130 K, too cold for a stellar companion. The luminosity requires an emitting area of 4–40 AU², too large for planets. Only an extended object, such as a dust disk, can explain these properties. The location of the dust, 40–100 AU, corresponds to the location of the Kuiper Belt in the solar system, and the dust disk was suggested to originate from collisionally disrupted Kuiper Belt-like objects (KBOs) that were dynamically rejuvenated in the AGB and post-AGB evolutionary stages of the central star (Su et al. 2007).
To search for more dust disks similar to that around the WD in the Helix Nebula, we have carried out a Spitzer MIPS 24 µm survey of 72 hot WDs. The results of this survey have inspired us to search the Spitzer archive for central stars of planetary nebulae (CSPNs) with IR excesses. Here we present the results of the 24 µm survey and the Spitzer archival search. In addition to dust disks produced by KBO collisions, we also consider other scenarios that could produce IR excesses, such as remnants of post-AGB binary disks or H-poor compact nebulosities produced in born-again planetary nebulae (PNe).

2. Spitzer MIPS 24 µm Survey of Hot WDs
Could the dust disk around the Helix central star be a common phenomenon? Dust disks around low- and intermediate-mass main sequence stars have been identified via IR excesses in many surveys (e.g. Rieke et al. 2005; Bryden et al. 2006; Beichman et al. 2006; Trilling et al. 2008), and the dust in these disks is produced by collisions in planetesimal belts (Rieke et al. 2005), the same mechanism as suggested for the Helix dust disk. KBOs at 40–100 AU are sufficiently far to survive through stellar evolution (Debes & Sigurdsson 2002), and therefore, dust disks around WDs could be common.

These dust disks can, however, be detected through their IR emission only for a limited time. Figure 1 shows curves of constant dust temperatures as a function of WD’s effective temperature and the dust’s orbital radius. This figure demonstrates that only the hottest WDs ($T_{\text{eff}} \approx 100\,000$ K) can sufficiently heat the dust at 40–100 AU to emit in the mid- to far-IR wavelengths, where they would be detectable with Spitzer. As the WDs cool, the dust temperatures drop, shifting the peak of excess emission out of the Spitzer wavelength range. Furthermore, the collisional rate decreases with time, and the dust disk will eventually dissipate below the detection limit.

We have therefore selected hot, young WDs for the Spitzer 24 µm survey. Out of 72 targets, 34 are still CSPNs, and are the closest analogs of the Helix Nebula and its central hot WD. The remainder of our sample included hot WDs with the broadest possible range of spectral classes.

We observe unresolved emission coincident with the WD in 7 cases, all of them in PNe. In 5 additional cases, the possible point source is superposed on a bright nebular background. We have constructed SEDs of these WDs using optical and near-IR values from the literature. All 7 clear detections show excess emission at 24 µm.

Figure 2 shows examples of images and SEDs of WDs with 24 µm excesses. WD 0726+133 is the central star of the PN Abell 21. Its SED from optical to IRAC 4.5 µm can be well approximated a blackbody with WD’s effective temperature ($140\,000$ K, Werner et al. 1997). The 24 µm flux is, however, $\sim 1500$ times higher than the expected value. The upper limit on the dust temperature imposed by nondetection at 5.8 and 8.0 µm is $\sim 120$ K. Given the effective temperature of the WD, the dust would be heated to 120 K at a distance of $\sim 50$ AU. The emitting area required to account for the 24 µm flux is $\sim 4$ AU$^2$. These values are very similar to the properties of the dust disk around the Helix CSPN. While further observations are still needed to confirm the nature of the mid-IR emitter and constrain the SED at longer wavelengths, Abell 21 likely has a dust disk similar to that of the Helix CSPN.

Another dust disk candidate with SED similar to that of Helix CSPN is the central star of EGB 1, WD 0103+732. Optical and near-IR data points follow the blackbody tail of the hot central WD ($T_{\text{eff}} = 147\,000$ K, Napierowski 2001), and the MIPS 24 µm flux is $\sim 3700$ times higher than the expected value. Follow-up IRAC observations from Spitzer’s Cycle 5 show that IRAC 3.6, 4.5 and 5.8 fluxes lie on the blackbody tail, but the 8 µm data point shows flux $\sim 60$ times higher than expected. The IR excess can be fitted by a blackbody with a temperature of 170 K and an emitting area of $\sim 5$ AU$^2$. The dust temperature corresponds to the distance of $\sim 40$ AU from the central star. This CSPN also likely possesses a dust disk similar to Helix CSPN.

WD 0950+139, the CSPN of EGB 6, shows an SED that is somewhat different from that
Figure 1. Curves of constant dust temperature in the $T_{\text{eff}} - D$ (effective temperature - distance) parameter space. The dust temperatures and corresponding blackbody peak wavelengths are labelled. Dust temperatures ($T_{\text{dust}}$) are related to $D$ and $T_{\text{eff}}$ via $T_{\text{dust}} = (1 - a)^{\frac{1}{4}} \sqrt{\frac{R}{D}} T_{\text{eff}}$, where $a$ is dust’s albedo and $R$ is the stellar radius. We have used the value of 0.1 for $a$, typical of asteroids and cometary dust, and $R_{\odot}$ for stellar radius, representative of WD radii. The dust at distances of 30–100 AU from the star will peak in mid-IR (24–70 $\mu$m) only if its central star is very hot (>80,000 K).

of the Helix CSPN. Emission in excess of the central star can be seen in J, H and K bands as well as at 24 $\mu$m, unlike the Helix CSPN, which showed excess starting from 8 $\mu$m. In addition, optical observations of this CSPN revealed a strong emission line component superposed on the continuum emission from the central WD. A spectrum of the sky 10$''$ N from the PN nucleus did not show any emission lines, thus suggesting that they arise in a compact unresolved nebulosity around the central WD (Liebert et al. 1989). High-resolution HST emission-line images revealed that the emission actually originates from a point-like source that is offset from the PN nucleus by 0.18$''$ (120 AU), and later continuum images confirmed the presence of a dM companion (Bond 1994). A dM ($T_{\text{eff}} \approx$ 2000 K) star can account for the near-IR excess, but not the MIPS 24 $\mu$m excess. It has been suggested that the companion has accreted material from the progenitor of WD0950+139 and that this accretion disk is responsible for the nebular line emission (Bond 1994). The emission at 24 $\mu$m suggests that dust is likely present either around the WD or the dM companion, but IR spectra are needed to assess the nebular line contribution to the 24 $\mu$m emission.

3. Spitzer Archival survey of CSPNs
Interestingly, all hot WDs that exhibit 24 $\mu$m excesses are very young, still surrounded by PNe. Inspired by the prevalence of PN environment for hot WDs showing mid-IR excesses, we have used archival Spitzer IRAC (3.6, 4.5, 5.8, and 8.0 $\mu$m) and MIPS (24, 70, and 160 $\mu$m) observations of PNe to search for CSPNs with IR excesses.
Figure 2. Spitzer 24 µm images (top) and SEDs (bottom) of three hot WDs from the 24 µm survey that exhibit 24 µm excesses. Each panel is labeled with WD and PN names, passband, and image scale. The SEDs are constructed with optical photometry from McCook & Sion (1999), 2MASS JHK, IRAC photometry (where available) and Spitzer MIPS 24 µm data.

We have examined images of 55 resolved PNe, and selected 13 in which the nebular emission was not too confusing or dominant in the central region, and the CSPN was detected in most IRAC bands. For these 13 cases, we have carried out photometric measurements. Supplemented with optical fluxes and near-IR photometry from 2MASS, we have constructed SEDs for these targets, and fitted them with blackbody curves. Four CSPNs show clear excess emission in the IRAC bands, and one shows excess in the MIPS 24 µm band.

The images and SEDs of three of these CSPNs are shown in Figure 3. The SED of NGC 2438 shows excess emission starting from the J-band across all IRAC bands. Furthermore, NGC 2438 was also imaged in the MIPS 24 µm survey of hot WDs, and the IR flux from the central source is ~6 orders of magnitude higher than what is expected from the CSPN alone. The excess emission in JHK and IRAC 3.6, 4.5 and 5.8 µm bands can be fitted by an M3 dwarf (0.5 R☉, 3470 K). The IR excess at 8 and 24 µm can be fitted with a 120 K dust disk with an emitting surface area of ~1000 AU².

In the case of NGC 6804, prominent IR excess is seen over the entire 1–8 µm range plotted. Fitting of the IR excess requires more temperature components (~1500 K, ~600 K), likely indicating a range of dust temperartures, if dust continuum is indeed the source of the observed IR emission. The SED does not exclude the possible presence of a cool (T_{\text{eff}} \approx 1500 K) companion; however, a companion alone cannot account for all of the observed excess, and furthermore, no companion has been detected around this CSPN (Ciardullo et al. 1999).

The CSPN of NGC 7139 is too faint to be detected in 2MASS, but is clearly seen across all IRAC bands. We have used the faintest stars detected near the CSPN to place upper limits on the CSPN’s JHK fluxes. The stellar emission was modelled based on the CSPN’s effective temperature (125 000 K) and B magnitude from Walton et al. (1990). The SED shows clear
Figure 3. IRAC 8 μm images (top), and SED plots (bottom) of NGC 2438 (left), NGC 6804 (center), and NGC 7139 (right). The hot CSPNs are marked with crosslines. Image scales are marked in each panel. The data points in SEDs represent optical fluxes gathered from Ciardullo et al. (1999), Acker et al. (1990), Gathier & Pottasch (1988) and Walton et al. (1990) near-IR fluxes from 2MASS, and IRAC and MIPS photometry. The CSPN of NGC 7139 was below 2MASS detection limit, and the plotted upper limits represent fluxes of the faintest stars in the surrounding field of view.

excess in all IRAC bands, and can be fitted with a 1500 K blackbody for an emitting area of 0.002 AU$^2$. A 1500 K brown dwarf alone cannot account for all of the observed excess, as the emitting area required is higher than what a brown dwarf can provide.

4. Possible Origins of IR excesses
The IR excess of a given WD/CSPN is a necessary, but not sufficient, condition to conclude that the star is surrounded by a dust disk. Indeed, the differences between the SEDs of our targets imply different properties of the disks, if not even different origins of excess emission. We therefore need to consider other potential mechanisms that can produce IR excess.

4.1. Post-AGB Binary Evolution
It has been suggested from an analysis of broad-band SEDs of 51 post-AGB stars that Keplerian rotating dust disks are commonly present around binary post-AGB stars (De Ruyter et al. 2006). van Winckel (2003) showed that post-AGB stars displaying SEDs of warm dusty disks are all single-lined spectroscopic binaries. A tight correlation between the presence of hot dust and a binary companion (Waters et al. 1997, van Winckel et al. 1999) suggests that the hot dust persists in the system because it is trapped in a stable circumstellar or circumbinary orbit (van Winckel 2003).

The 7 hot WDs with 24 μm excesses from our survey and the 5 CSPNs with IRAC and/or MIPS excesses found in the Spitzer archive are all in PNe and thus represent the youngest
WDs that have just evolved past the post-AGB phase. One of them (NGC 2346) has a confirmed binary companion (Mendez & Niemela 1981) and SED that resembles those of post-AGB binaries; thus, one cannot help asking whether some of these 24 μm and/or IRAC excesses are also related to the IR excesses of binary post-AGB stars reported by De Ruyter et al. (2006). The fact that the near-IR SEDs of EGB 6 and NGC 2438 can be fitted by a cool companion, and the SEDs of NGC 6804 and 7139 do not exclude a companion lends support to this possibility. On the other hand, the SEDs of, e.g., the CSPNs of the Helix Nebula, Abell 21, and EGB 1 do not show any signature of a low-mass companion.

The binarity of AGB stars may play an important role in shaping the PNe they later produce, especially the bipolar PNe (Soker 1998; De Marco 2006). However, it is difficult to indentify and confirm the presence of a close companion of a CSPN via direct imaging (e.g., Ciardullo et al. 1999); furthermore, irregular spectral variations due to winds hamper the detection of periodic radial velocity variations (De Marco et al. 2007). If a dust disk trapped in a stable orbit around a binary system persists throughout the PN phase, its presence can serve as a powerful diagnostic for the binarity of a CSPN, and further our understanding of the role of binaries in the shaping of PNe.

4.2. Compact Unresolved Nebulosity

Spitzer’s MIPS and IRAC passbands contain a number of spectral lines, for example, [Ar II] λ6.98 μm and [Ar III] λ8.99 μm in the IRAC 8 μm band, and [Ne V] λ24.32 μm and [O IV] λ25.89 μm in the MIPS 24 μm band. It is possible that the IR excesses of the hot WDs and CSPNs originate from these nebular lines, as for the rest of the PNe. In such a case, the central diffuse emission must be associated with density enhancement, but density enhancement is not expected near the centers of a large evolved PNe, unless they are born-again PNe like Abell 30 and Abell 78.

Abell 30 and Abell 78 are two large and faint PNe with hot nuclei that were both found to exhibit IR emission at 10 and 18 μm (Cohen & Barlow 1974). This central emission originates from knots seen in [OIII] λ5007 Å and He II λ4686 Å, but undetected in Hα (Jacoby 1979; Hazard et al. 1980). This observed morphological difference was suggested to be caused by H depletion in the central region (Jacoby & Ford 1983), which occurs in a born-again PN whose WD experiences a final thermal pulse during which H is completely burnt (Iben et al. 1983). It is possible that some of the observed IR excesses originate from an unresolved H-depleted nebulosity, thus, spectroscopic observations are necessary to unambiguously assess the nature of a mid-IR excess.

5. Future Work - Follow-up Observations

For a number of targets, we have very few, sometimes only one, data point in excess of the expected WD’s photospheric emission. With multiple possible origins of the excess, it is imperative that we characterize the excess emission over a wider wavelength range, and carry out observations that would serve as diagnostics to distinguish among the possible origins. Some of these observations are outlined below.

5.1. Infra-Red Spectra and Photometry

CSPNs are, by definition, surrounded by ionized nebulae, and thus nebular emission lines will be present in the IRAC and MIPS bands. Spectral observations are therefore crucial to separate the dust continuum from the line emission and to evaluate their relative contributions to the observed excesses. We were awarded Spitzer priority 1 time to get IRS spectra and additional IRAC and MIPS imaging of CSPNs K 1-22, EGB 1, Sh 2-188 and Sh 2-216 and priority 3 time for CSPNs NGC 2438, NGC 6804 and NGC 7139. The extended SED coverage, provided by additional IRAC and MIPS observations, will help us better constrain the the SED and find the range of
temperatures in the disk. With reasonable assumptions on grain properties (size distribution and composition), these observations will allow us to determine the radial distribution of the disk, which can help us differentiate between dust originating from binary post-AGB evolution or KBO collisions. The most interesting aspect of the spectra is, however, the possible detection of mineralogical features of dust grains. For example, if the silicate emission feature at 10 \( \mu m \) is detected, connections with crushed asteroids can be made.

5.2. High-resolution Optical Imaging

The Spitzer spectra will allow us to distinguish between the dust continuum and nebular line contributions to the excess IR emission, but Spitzer’s angular resolution limits our ability to conclude definitively whether the excess emission is associated with the CSPNs, their companions, or chance superposition of background sources. High-resolution view of the region within Spitzer’s point spread function is therefore needed to properly interpret the IR observations.

Broad-band imaging would provide the clearest view of continuum sources in the vicinity of the WDs with IR excesses and should thus help us find previously unresolved companions or background galaxies. Narrow-band nebular line (H\( \alpha \), [O III] and He II) images would allow us to diagnose the compositions of the ionized gas in the central region. H-deficient gas would be present in the [O III] and He II images, but not in H\( \alpha \) images. Comparisons between H\( \alpha \) and [O III] images will therefore reveal the presence of H-deficient ejecta such as those observed at centers of born-again PNe.

5.3. High-dispersion Optical Spectroscopy

High-dispersion (R\( \sim \)30,000) echelle spectroscopy of hot WDs and CSPNs with IR excesses can help us find spatially unresolved emission line sources and measure their velocities. The receding and approaching sides of the PN should average to the WD velocity. An unresolved nebula centered on the WD would have the same central velocity but a different FWHM, and a nebula centered on a companion would have a different central velocity from the WD. If the H\( \alpha \) component is absent at velocities corresponding to these emission lines, H-poor ejecta is likely present.

In addition, the high-dispersion echelle observations would also help us search for unresolved companions of the hot WDs and CSPNs. Hot WDs may show a non-LTE inversion in the H\( \alpha \) absorption line, such as the one seen in the Helix central star. Monitoring temporal variations of stellar H\( \alpha \) profiles could help us search for companions, similar to the work done for the Helix central star (Gruendl et al. 2001).

6. Summary

The discovery of a dust disk around the CSPN of the Helix nebula through its 24 \( \mu m \) excess has inspired us to conduct a Spitzer 24 \( \mu m \) survey of hot (\( T_{\text{eff}} \approx 100\,000 \) K) WDs. Out of 72 targets observed, 7 show 24 \( \mu m \) excesses, all of them in PNe. To find more cases of CSPNs with IR excess, we have searched the Spitzer archive, and found 4 targets with IRAC excesses, and 1 additional target with MIPS 24 \( \mu m \) excess. While some SEDs are similar to that of the Helix CSPN and show excess emission only at wavelengths longwards of 8 \( \mu m \), others show excess starting at shorter wavelength.

The dust around the Helix central star was suggested to be produced by collisions among KBOs (Su et al. 2007). However, other mechanisms that could produce IR excess need to be considered as well. Since 24 \( \mu m \) excesses were found only in CSPNs, it is possible that the observed dust is a remnant from disks formed during post-AGB binary evolution. If the IR excesses originate from nebular emission lines, the central emission enhancement suggests a
presence of compact nebulosity, which is not expected in large, evolved PNe, unless they are born-again PNe. More observations, such as IR spectra, high-resolution imaging, or high-dispersion optical spectroscopy, are needed to help us identify the origins of these IR excesses.

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