THE MORPHOLOGY OF DUST EMISSION IN PLANETARY NEBULAE AND PROTO–PLANETARY NEBULAE

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Abstract. This review covers recent results from ground based mid-infrared (mid–IR; 8–25μm) imaging of thermal dust emission. The mid–IR images of proto–PNe show evidence for axially symmetric superwinds. In young PNe, the dust appears to be well mixed with the gas in the ionized gas regions. In carbon rich PNe and proto–PNe, the 11.3μm feature attributed to PAHs appears more spatially extended than "continuum" dust emission and the near–IR (1-3μm) excess appears spatially coincident with mid–IR dust emission. This review is not meant to cover the broader topic of dust in PNe and proto-PNe and we refer the reader to (Barlow 1993) for the most recent broad review.

1. Introduction

Most of our information on circumstellar dustshells of planetary nebulae (PNe) and proto-planetary nebulae (proto–PNe) comes from the IRAS data base and ISO will certainly improve our knowledge (Cox et al. 1997); (de Graauw et al. 1997). However, both satellites suffer the same limitation of low angular resolution (IRAS $\sim 1'$; ISO$\sim 6'' - 1'$) and thus cannot resolve the structure of the dust emission in most of these objects. Ground based mid–IR imaging, which has experienced a technological boom, offers angular resolutions of $\sim$1$''$ on 3–4 m class telescopes and has the potential to achieve 0.$''$2 resolution on 8–10 m class telescopes coming on line. These mid–IR images reveal the geometry of the inner regions of the dust shells which samples the most recent phase of mass loss and the region from where the bulk of the infrared luminosity arises.

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2. Observations

Approximately 100 PNe and proto-PNe have been imaged at mid–IR wavelengths (8–25μm) using several different mid–IR cameras (Berkcam-, MIRAC2, TIMMI, MANIAC). The angular resolution is typically 1″ which means that we can obtain physical resolutions of 1.5×10^{16}cm at 1 kpc. The spectral resolution is typically $\frac{\Delta\lambda}{\lambda} \sim 1 - 10\%$ which means that we can take images of pure dust emission that is uncontaminated by ionized gas lines. The sensitivity of ground based observations is limited by the tremendous sky background which is 10^5 times brighter than the typical source emissions. Hence, our observations are limited to sources brighter than ~1 Jy (although sources of 100 mJy are possible) and hence we sample nearby ($<$ 5 kpc) proto–PNe and young PNe which have fairly compact dust shells that are hot enough ($>$100 K) to emit in the mid–IR. Large/evolved PNe, which have cool dust shells ($\sim$ 50 K), are too faint to be observed from the ground; however, some are large enough to resolve with IRAS and ISO e.g. the Helix (Cox et al. 1997); (Hawkins & Zucker man 1991); (Young et al. 1993). Of these 100 circumstellar dustshells that have been imaged in the mid–IR: ~15% are well resolved showing good detail of the 2-D projected geometry (e.g. IRAS 07134+1005); ~45% are marginally resolved permitting some detail of the 2-D projected geometry, most importantly a constraint on the inner radius of the dust shell (e.g. IRAS 22272+5435); and ~40% are unresolved which provides an upper limit for the inner radius of the dust shell (e.g. IRAS 04296+3429). The work on these mid–IR images is in progress and below we describe some of the current findings.

3. Proto–PNe

Probably the most exciting mid–IR images are those of proto–PNe because they may reveal the geometry of these nebulae before they have been heavily processed by the shocks and hardening radiation inherent in planetary nebula formation. Are the proto–PNe axially symmetric as we find the majority of PNe? Yes, all those proto–PNe that have been resolved have an axial symmetry (Meixner et al. 1997); (Skinner et al. 1996); (Hawkins et al. 1995); (Hora et al. 1996); (Skinner et al. 1994); (Molster et al. 1997); (Kömpe et al. 1997); (Dayal et al. 1997); (Deutsch 1990); (Hora 1991); (Meixner 1993). Among these, there appears to be two types of sources. (1) Proto–PNe with optically thin dust emission ($\tau_{10\mu m} \sim 0.001 - 0.01$) show rings and/or limb brightened peaks suggestive of equatorial toruses (e.g. HD 161796, IRAS 07134+1005, GL 2343). (2) Proto–PNe with optically thick dust emission ($\tau_{10\mu m} > 1$) show compact cores and extended mid–IR emission that coincides with the bipolar optical reflection nebulosity (e.g. GL 2688, GL618 and GL915). General conclusions about the statistics of proto–PNe geometries awaits the analysis of a larger sample of proto–PNe. However, there appears to be no correlation of morphology with circumstellar chemistry (i.e. carbon vs. oxygen rich envelopes) as initially suspected (Meixner et al. 1993).

To interpret these clearly axially symmetric proto–PNe dust shells, we are using an axially symmetric dust code based on the work of (Collison & Fix 1991). The geometry of the circumstellar dust shell (Figure 1) assumes a core component that is axially symmetric and a halo component that is spherically symmetric. This working model is loosely based on the OH maser evidence for spherical symmetry for the initial AGB wind (Habing & Blommaert 1993) and the mid–IR image evidence for axially symmetric structures in proto–PNe as well as the abundant evidence for axially symmetric structures in PNe. In this dust code, the central star heats the circumstellar dustshell which in turn radiates in the infrared, and the circumstellar dustshell reddens the starlight. The mid–IR emission arises from the central parts of the dust shell only. Using our mid–IR images and optical to IR photometry, we have constrained models for six proto–PNe (Meixner et al. 1997);(Skinner et al. 1996). For IRAS 07134+1005 (Figure 2; cf. (Meixner et al. 1997)), we have derived an equator–to–pole mass loss ratio of 18 during the superwind phase, a superwind to AGB wind mass loss ratio of 23 and a superwind mass loss rate of $\sim 6 \times 10^{-5}$ $M_\odot$ yr^{-1}.

4. Young PNe

The morphology of the compact young PNe can be obtained from radio interferometry and hence the mid–IR images do not bring as great a revelation as they do for proto–PNe. Nevertheless, mid–IR images of young PNe offer a continuity in viewpoint between the proto–PNe and PNe stages of evolution and they provide an important comparison with the radio images. As we find with the proto–PNe, mid–IR images of young PNe show an axial symmetry for the dust emission (Arens et al. 1984),(Hora et al. 1990),(Hora et al. 1993), (Meixner et al. 1993), (Meixner et al. 1996). Comparison of the mid–IR dust emission and the radio continuum emission shows that the mid–IR dust emission morphology is *not* identical to the radio continuum morphology (Meixner et al. 1996);(Meixner et al. 1997). In general, the mid–IR dust emission is more compact than the radio continuum emission. M 2-9 is an extreme example where the mid–IR emission arises in the compact ($<1''$) core of the extended ($\sim45''$) bipolar morphology observed in the radio. The mid–IR images of young PNe trace the thermal dust emission while the radio continuum images trace the free-free emission in the ionized gas. Does this mean then that the dust and ionized gas are not well mixed? Absolutely not. In order to determine the radial abundance of any

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constituent, gas or dust, we must first calculate the radiative transfer to determine if the radial gradient of emission is an excitation gradient or an abundance gradient.

For one well studied case, IC 418, we find the mid–IR emission to be slightly smaller in size than the radio continuum and to have a markedly different morphology (Meixner et al. 1996). In order to understand these differences, we used a radiative transfer code developed by Harrington et al. (1988) to model the dust and ionized gas emission (cf. (Hoare 1990)). This code assumes spherical symmetry, but solves for both the gas and dust radiative transfer and includes ionized line emissions (e.g. Lyman α) in addition to starlight into the dust heating budget. We assume that the dust and gas is well mixed. Under this assumption, we find that the mid–IR dust emission and the radio continuum emission spatial distributions are reproduced within the errors of the spherically symmetric assumption. Hence we conclude that the dust and ionized gas are well mixed. The mid–IR dust emission appears more compact than the ionized gas emission because the dust is hotter closer to the star. The IR dust emission depends linearly on the column density of dust, but depends on the dust temperature as T^5 assuming a λ^{-1} emissivity function for the dust. The radio continuum emission depends primarily on the emission measure (n_e^2L) and not on electron temperature which is approximately constant over the nebula.

5. The 11.3μm Dust Feature in Carbon Rich Objects

Carbon rich young PNe and proto–PNe have a number of mid–IR features which have been attributed to polycyclic aromatic hydrocarbons (PAHs) (Allamandola et al. (1989));(Leger & Puget 1984) and the 11.3μm feature is one of them. Mid–IR images of both young PNe (e.g. BD +30°3639, (Hora et al. 1993)) and proto–PNe (GL915/Red Rectangle (Hora et al. 1996); IRAS 22272+5435 (Meixner et al. 1997)) show that the 11.3μm feature emission is more extended than the underlying dust continuum. At present, we do not understand why the 11.3μm emission is more extended. However, it is either due to an abundance gradient of the PAHs or, more likely, an excitation gradient where the 11.3μm dust carriers can be excited by optical photons which penetrate further into the dust nebula (Schutte et al. 1993).

Another, more mysterious feature near 21μm is found only in carbon rich proto–PNe (e.g. IRAS 07134) suggesting a short lifetime for its carrier because it is not found in young carbon rich PNe (Kwok et al. 1989); (Justtanont et al. 1996). Here mid–IR imaging studies could help understand the 21μm feature emission. Does the 21μm emission arise in the same region as the underlying dust continuum? Or is it more extended like the 11.3μm feature emission?

In the young carbon rich PNe, excess emission at near–IR (1-3μm) wavelengths is observed and attributed to small, hot (~1000 K) dust grains (e.g. (Willner et al. 1979)). The spatial distribution of this near–IR excess emission is coincident with the mid–IR dust continuum emission in IC 418 ((Meixner et al. 1996)), BD+303639 ((Hora et al. 1993)) and IRAS 21282+-5050 ((Meixner et al. 1993)). The similarity suggests a similar type of dust. Allamandola et al. (1989) suggest the existence of a near–IR vibrational, quasi–continuum for all types of PAHs and perhaps we are observing this quasi–continuum in these young carbon rich PNe.

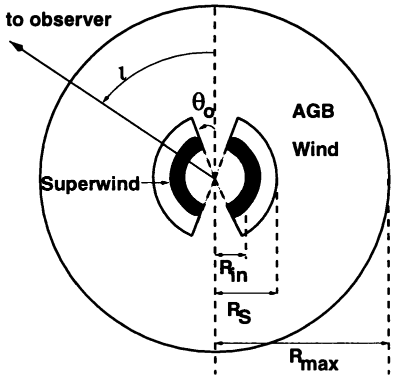

Figure 1. Schematic of the axially symmetric dust code geometry. The shaded region shows that part of the dust shell which emits at mid–IR wavelengths. From Meixner et al. (1997).

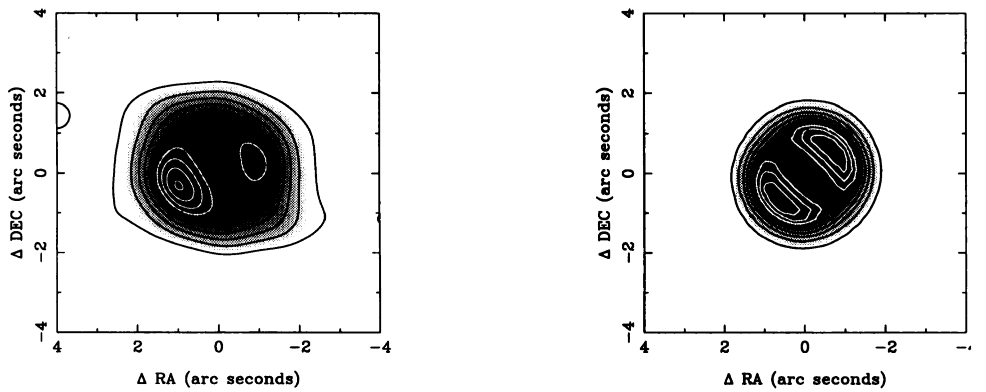

Figure 2. IRAS 07134+1005, a carbon rich proto–PNe, with a 21μm feature. The left figure shows a deconvolved observed image of the toroidal dust shell at 11.8μm and the right figure shows a best fit model image at 11.8μm. From Meixner et al. (1997).

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