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2.5 Dimensional Radiative Transfer Modeling of Proto-Planetary Nebula Dust Shells with 2-DUST

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Abstract. Our observing campaign of proto-planetary nebula (PPN) dust shells has shown that the structure formation in planetary nebulae (PNs) begins as early as the late asymptotic giant branch (AGB) phase due to intrinsically axisymmetric superwind. We describe our latest numerical efforts with a multi-dimensional dust radiative transfer code, 2-DUST, in order to explain the apparent dichotomy of the PPN morphology at the mid-IR and optical, which originates most likely from the optical depth of the shell combined with the effect of inclination angle.

1. Axisymmetric PPN Shells and Single Density Distribution Model

Since the PPN phase predates the period of final PN shaping due to interactions of the stellar winds, we can investigate the origin of the PN structure formation by observationally establishing the material distribution in the PPN shells, in which pristine fossil records of AGB mass loss histories are preserved in their benign circumstellar environment.

Our mid-IR and optical imaging surveys of PPN candidates in the past several years (Meixner at al. 1999; Ueta et al. 2000) have revealed that (1) PPN shells are *intrinsically* axisymmetric most likely due to *equatorially-enhanced* superwind mass loss at the end of the AGB phase and (2) *varying degrees* of equatorial enhancement in superwind would result in different *optical depths* of the PPN shell, thereby heavily influencing the mid-IR and optical morphologies.

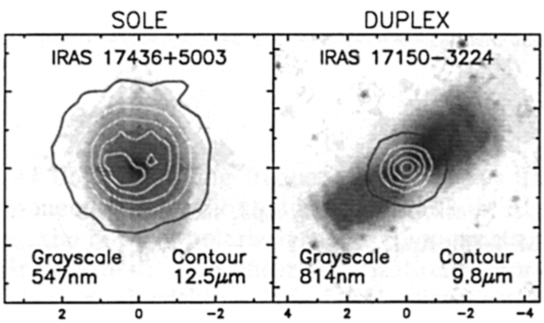

Fig. 1 Two edge-on PPNs with two morphologies.

In fact, an *edge-on* PPN can assume completely different morphologies depending on the optical depth of the dust shell: an *optically thin* dust shell reveals its limb-brightened edges of the dust torus in the mid-IR (SOLE type; left in Fig. 1), while an *optically thick* shell simply appears as a dust lane that separates "classic" bipolar lobes in the optical (DUPLEX type; right in Fig. 1).

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2. Optical Depth as a Source of the PPN Morphological Dichotomy

We have developed a dust radiative transfer code, *2-DUST*, to explain the PPN morphological dichotomy by varying degrees of equatorial enhancement. With 2-DUST, radiative transfer is iteratively computed by tracing rays in a 3-D space in a 2-D axisymmetric grid, requiring the luminosity constancy at each radial grid. The code treats dust absorption/emission and (an)isotropic scattering for a given set of dust species, each having distribution of sizes (e.g., Ueta et al. 2001a,b and Meixner et al. 2002). For our analysis, we have employed a particular density function that consists of an innermost superwind dust torus, an elliptical mid-region, and an outer spherical AGB wind shell.

With this density function, we have reproduced the characteristic PPN morphologies of dust emission and scattering by varying the optical depth of the shell (Fig. 2). Our results show that mid-IR images provide especially useful diagnostic of the shell geometry for optically thin cases. Mid-IR images play an especially crucial role in constraining the inner shell radius, and hence, the dust temperature and other physical conditions in the shell. Thus, at least 2-D radiative transfer calculations fitted with *both* mid-IR and optical images are necessary to securely derive the inclination angle of the PPN dust shells.

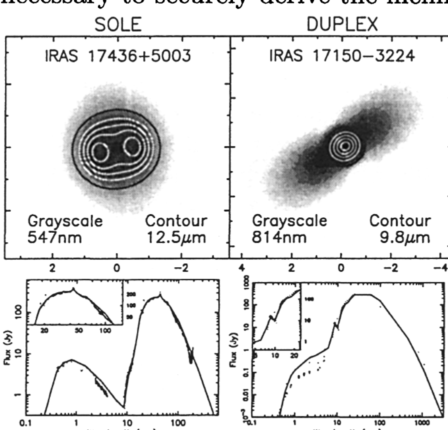

Fig. 2 2-DUST model maps and SED of SOLE (left) and DUPLEX (right) PPNs.

	IRAS 17436	IRAS 17150
$L_*(L_\odot)$, $T_*(K)$	2800, 7000	27000, 5200
$R_{\rm min}$ (cm)	11.2×10^{15}	9.7×10^{15}
Inclination	$\sim 90°$	$\sim 82°$
$T_{\rm dust}$ (K)	112	222
$\tau_{9.8\mu{\rm m,eq}}$	0.46	12.0
$\rho_{\rm eq}/\rho_{\rm pole}$	9	160
$M_{\rm shell}(M_\odot)$	0.7	4.9
$\dot{M}_{\rm AGB}(M_\odot/{\rm yr})$	4.1×10^{-5}	1.9×10^{-4}
$\dot{M}_{\rm SW}(M_\odot/{\rm yr})$	4.2×10^{-5}	3.0×10^{-3}
$a_{\rm min}(\mu{\rm m})$	0.2	0.001
Composition	amor. sil. crys. sil. H_2O ice	amor. sil.

Tab. 1 Selected model parameters.

Besides the three dimensional shell parameters including the inclination angle, we can also derive various physical quantities from the radiative transfer calculations, which would provide clues for the mechanism(s) of the axisymmetric mass loss on the AGB as well as for the nature of progenitor stars. We are continuing our numerical analysis on our entire imaging survey samples to derive the *mean properties* of the PPN dust shells.

References

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