
Probing the “Missing Mass” in Bipolar and Multipolar Pre-Planetary Nebulae

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Summary. We present results from a study using the IRS, IRAC and MIPS instruments on Spitzer, to determine the spectral energy distribution (SED) over the $\sim 3\text{--}100\ \mu\text{m}$ range for a subsample of pre-planetary nebulae (PPNe) observed in our HST surveys of these transition objects and derive the nebular masses. We find amorphous silicate absorption features (indicative of very large optical depths) and crystalline silicate emission features (suggesting grain processing in long-lived disks) in a majority of our objects.

Key words: pre-planetary nebulae, planetary nebulae, stars: AGB and post-AGB, mass-loss, circumstellar matter, dust

1 Introduction

The formation and shaping of planetary nebulae (PNe) is probably the most exciting problem in the late evolution of $1\text{--}8M_{\odot}$ stars. Sahai & Trauger proposed in 1998 that collimated fast winds or jets (hereafter CFWs), operating during the PPNe or very late-AGB phase, are the primary agent for producing asymmetric shapes in PNe [6]. Thus PPNe hold the key to understanding the development of aspherical structure in PNe. HST imaging surveys of PPNe [7] show the *result* of the jet-envelope hydrodynamic interaction in the form of elongated lobes with tenuous interiors and dense walls. But, the jets are seldom seen directly, due to the ubiquitous presence of the dense AGB circumstellar envelopes (CSE) into which the jets expand.

Numerical simulations of jets with such envelopes are therefore needed to *infer* the properties of the jets and understand the shaping process in detail [4]. However, a crucial input for such modelling is a knowledge of the density (and thus the mass and size) of the CSEs in PPNe, which we lack (except for a few well-studied objects). Nebular masses also provide an important lower limit on the mass of the progenitor star. Hence, with the primary goal of determining nebular masses, we have carried out Spitzer observations to determine the SED over the $\sim 3\text{--}100\ \mu\text{m}$ range for a subsample of PPNe observed in our HST surveys, excluding objects for which ISO spectra are already available. A second goal of our study is to obtain data

on specific spectral features (e.g., silicate and ice absorption features) which act as probes of different structural components (equatorial disks/torii) and unusual physical processes (growth of icy grain mantles) in these objects.

2 Observations & Results

We obtained IRS, IRAC and MIPS data on a sample of 16 objects in order to characterize their SEDs over the 3.6–95 μm wavelength range. The IRS data were obtained using the SL2 (5.2–8.7 μm), SL1 (7.4–14.5 μm), SH (9.9–19.6 μm), and LH (18.7–37.2 μm) modules. The IRAC was used in subarray mode at 3.6 and 4.5 μm for photometric measurements. MIPS was mostly used in SED mode to obtain spectrophotometric data over the 55–96 μm range; for 3 sources which were too strong for SED mode, imaging with the 70 μm array was used for photometry. We find, in many of our sources:

1. *Amorphous silicate absorption features* at 10 and 18 μm (similar to those seen in the ISO spectra of very red OH/IR stars such as OH127.8+0.0). The silicate absorption lines are signatures of very large optical depths ($A_v > 50$) suggesting that they probably arise in dense dusty disks or tori, often seen as dark waists in bipolar and multipolar PPNe.

2. *Crystalline silicate emission features* in the 20–37 μm wavelength region. The

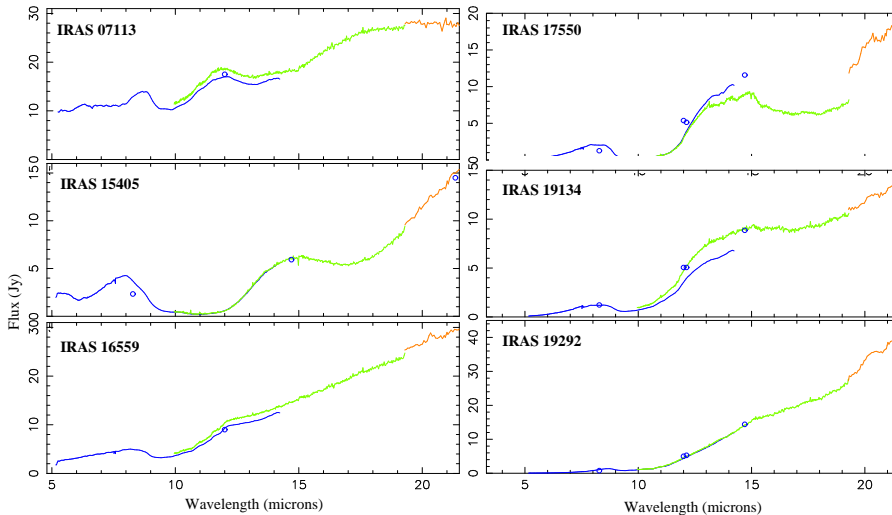


Fig. 1. PPNe with absorption features due to amorphous silicates. The blue, green and red curves show spectra taken with the SL, SH and LH modules of IRS; the circles show photometric data from IRAC, MSX and IRAS

best example of these is IRAS 16268, which has already evolved into a very young PN. The features we find have been observed in the ISO spectra of the young PN, NGC 6302 and identified as forsterite – and have $\lambda(\Delta\lambda=\text{FWHM})$ values of 19.56

(0.45), 23.7 (0.58), 27.5 (0.38), and 33.8 (0.98) μm [5]. Crystalline silicate emission appears to be quite common in our sample, and was first noted in the ISO spectra of specific post-AGB objects and young PNe. But the formation of these solids in the circumstellar environment of evolved stars is poorly understood. Although annealing of amorphous grains is one pathway, this process requires high temperatures (1000 K) and long time-scales (10^5yr). The latter require the presence of long-lived disks around the central stars – consistent with this idea, a sample of binary post-AGB stars which are believed to have circumbinary disks show the ubiquitous presence of crystalline silicate features [1].

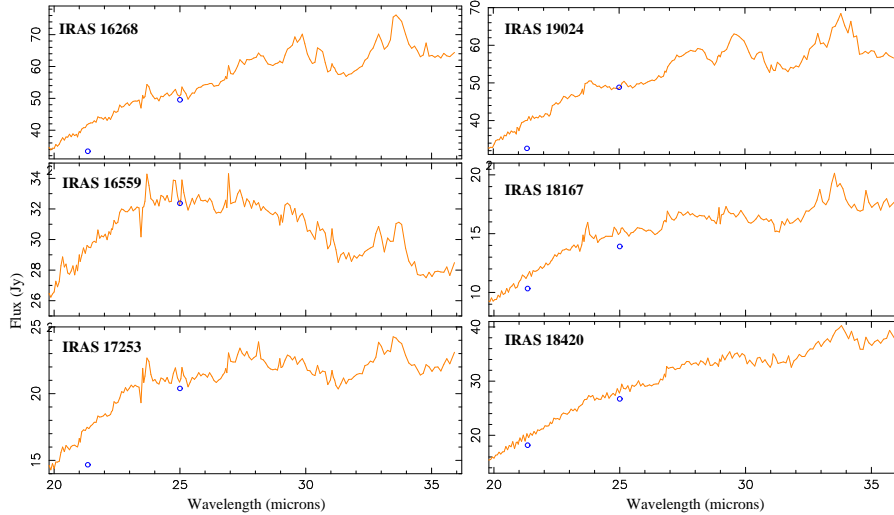


Fig. 2. PPNe with emission features due to crystalline silicates. Circles show photometric data from MSX and IRAS

3 Modelling

We have carried out preliminary modelling of the observed spectra using the DUSTY dust radiative transfer code [3]; we present results for two PPNe, IRAS 16559 and IRAS 19134. Both objects show small, bipolar nebulosities in their HST images with dense central waists [7]. In both cases we assume the central star to be a 7500 K black-body and find the best-fit simple model with an r^{-b} density shell ($b = 2$ for constant mass-loss rate at constant expansion velocity). The grain composition is assumed to be amorphous silicate grains with an MRN size distribution ($a \sim q^{-3.5}$, $a_{min}=0.005\mu\text{m}$, $a_{max}=0.25\mu\text{m}$). We find the dust temperature at the shell inner radius $T_d(\text{in})$, the radial optical depth A_v , the density power-law exponent b , and the size of the envelope, from the model fitting. The DUSTY model output is the SED normalized by the bolometric flux, and thus requires a distance, D , to scale it to absolute values for comparison with the data. By equating the model radial optical

depth to that derived from integrating the power-law density from r_{in} to r_{out} , we can find the dust mass in the shell (see, e.g., [8]). The total nebular mass is derived assuming a gas-to-dust ratio of 200.

1. IRAS 16559: We find a dust mass of $3.5 \times 10^{-3} M_{\odot}$ and a total mass of $0.69 M_{\odot}$ (we use $D=5.2$ kpc, assuming $L=6000 L_{\odot}$). Our best fit model requires $b = 1.5$, somewhat different from the results of our HST imaging, which gives $b = 1.8$ from an analysis of the scattered light halo due to the dusty CSE.

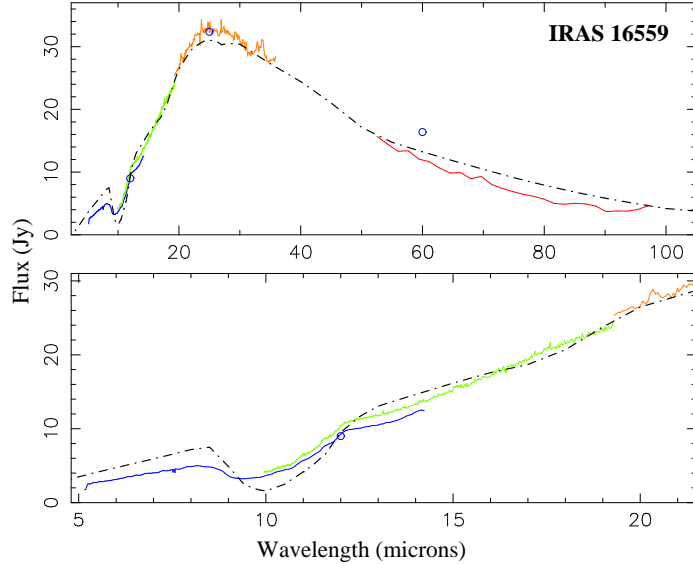


Fig. 3. Observed (*continuous curves*) and model (*dash-dot curve*) SED for the PPN, IRAS 16559. Blue, green, orange, & red curves show spectra taken with SL, SH, LH (IRS) & MIPS (SED) mode. Circle symbols as in Fig. 1

1. IRAS 19134: We find a dust mass of $3.8 \times 10^{-3} M_{\odot}$ and a total mass of $0.76 M_{\odot}$ for this “water-fountain” PPN. We use $D=8$ kpc derived from trigonometric parallax measurements using the VLBA [2].

4 Work in Progress

We will be developing more sophisticated dust models for our sources, which will allow us to include crystalline silicates as a separate component (not possible in the current version of the DUSTY code). We will investigate 2-component models (spherical shell + central disk/torus) in order to improve the quality of the fits in the 5–25 μm range.

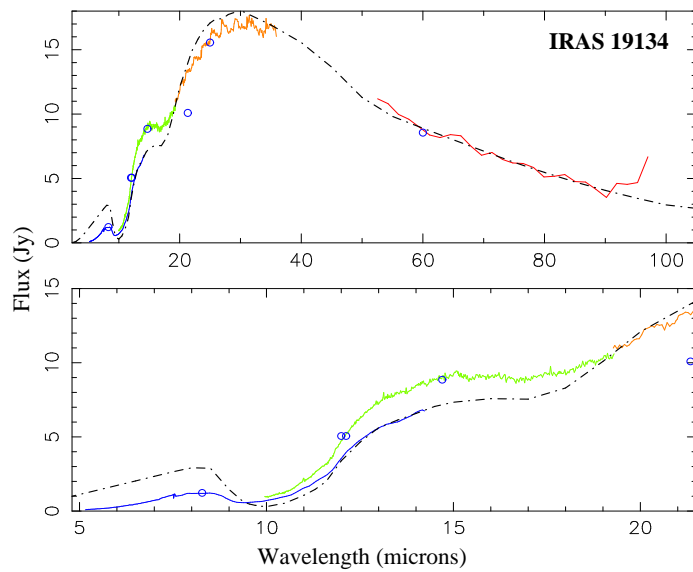


Fig. 4. Observed (*continuous curves*) and model (*dash-dot curve*) SED for the PPN, IRAS 19134

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