Planetary Nebulae in our Galaxy and Beyond
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Normal, Nascent and Stalled Pre-Planetary Nebulae

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Abstract. The formation and shaping of planetary nebulae (PNe) is probably the most exciting, yet least understood issue in the late evolution of (1–8)$M_\odot$ stars. PNe evolve from the envelopes of AGB stars through the supposedly very short ($\lesssim 10^3$ yr) pre-PN (or PPN) phase (Balick & Frank 2002). In 1998, in a radical departure from the then long-standing theoretical paradigm for PN formation, Sahai & Trauger (1998) proposed that as most stars evolve off the AGB, they drive collimated fast winds that sweep up and shock the AGB circumstellar envelope, producing the observed dramatic changes in circumstellar geometry and kinematics from the AGB to the PN phase. Pre-Planetary Nebulae (PPNs) have traditionally been understood as rare objects that represent a transitory phase in the evolution of AGB stars to PNs. In recent years, mainly due to high-resolution imaging surveys with HST, it has become possible to start studying the detailed physical properties for a statistically significant number of these objects. Here we provide a brief report of results from our several large surveys of PPNs with HST (and supporting ground-based observations).

Keywords. stars: mass loss, stars: AGN and post-AGB, ISM: jets and outflows

1. Surveys & Results

Our candidate PPNs have been selected based on very simple IRAS-color criteria, and are therefore not morphologically biased. In a previous survey of a smaller sample of PPNs (Ueta *et al.* 2000), objects were selected on the basis of non-uniform selection criteria. Our first set (normal PPN candidates) was constructed from catalogs of OH/IR stars (Sahai 2004). The IRAS spectral energy distributions (SEDs) of a large fraction of these objects indicate a lack of hot dust [12 to 25 μm flux ratio, $R(12/25) < 1$], implying a recent decrease in their mass-loss rates, marking the beginning of their post-AGB evolution. We therefore selected a flux-limited (at 25 μm) sample of objects with $R(12/25) < 1$ as candidate normal PPNs. A second set of objects (nascent PPN candidates) was constructed from published lists of AGB stars with detected heavy mass-loss, $\dot{M} \gtrsim 10^{-5} M_\odot$ yr^{-1} based on millimeter-wave CO data, and $3 > R(12/25) > 1$.

(a) Normal PPN candidates: A total of 52 objects were imaged. About 50% of these show resolved morphologies, all of which are aspherical. These aspherical morphologies cover a wide range of geometric shapes, which can be broadly classified as: bipolar, quadrupolar and multipolar. Furthermore, some objects show (1) clear point-symmetric structure, and/or (2) diffuse, round, surrounding halos, presumably the remnant mass-loss envelope of the progenitor AGB star. The observed sizes of most objects are consistent with expansion time-scales of several 100 to about 1000 yr, given a nominal range of distances (1–5 kpc), and expansion velocities typical of the fast molecular outflows observed in

PPNs (about 100 km s^{-1}). Optical spectroscopy of a limited number of these objects (Sahai & Sánchez Contreras 2004) shows dust reddened continuum spectra with little or no forbidden emission lines, confirming their pre-planetary nature. A significant fraction of these show Hα in emission, with very broad wings and blue-shifted absorption indicating the presence of fast (∼100 km s^{-1}) outflows.

(b) Nascent PPN candidates: A total of 48 objects were imaged. Compact, but non-stellar, structures are seen in about 35% of these. The remaining objects have point-source PSFs – since detailed PSF subtraction/removal has not been carried out in these objects, it is possible that additional objects may be found to possess extended structure. Aspherical structure is seen in the resolved objects. In some objects, a diffuse, round, surrounding halo is also seen, presumably representing the AGB mass-loss envelope. Discrete circular (partial) arc-like features are seen in some sources. The aspherical structure in the nascent PPN images is very different from that observed in normal PPNs, which show limb-brightened lobes. This structure could result from either (a) an aspherical density distribution in the imaged region, and/or (b) aspherical illumination. Case (b) would require the presence of relatively low-density channels close to the central star, which allow the starlight to escape preferentially along specific directions, and illuminate more distant regions of the circumstellar medium in an aspherical manner. In either case, the mechanism for creating the large-scale density inhomogenieties is likely to be high velocity outflows carving the AGB mass-loss envelope from the inside out.

(c) Stalled Pre-Planetary Nebulae: A small number of PPNs in our survey are quite large (e.g. IRAS19475+3119). A prime example of this phenomena is the well-studied Frosty Leo nebula in which the expansion age at the tips of its bipolar lobes is likely larger than 3500 yr (Castro-Carrizo *et al.* 2005) – yet its central star is quite cool (spectral type K7). For IRAS19475, which has an F3 central star, we find an age of 2400 yr. In the Red Rectangle, the age of the bipolar nebula is estimated to be 14000 yr (Cohen *et al.* 2005). Thus the evolution of the central stars of such long-lived PPNs appears to have been stalled.

In summary, PPNs are a unique probe of the late evolution of (1–8)$M_\odot$ stars. Understanding their properties (e.g., morphology, lifetimes, central star spectral types) is relevant to many challenging issues such as the launching of very fast jet-like outflows, the formation of massive, dense waists, and the stalled evolution of PPN central stars.

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