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Understanding the immediate progenitors of planetary nebulae

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Abstract. Pre-Planetary Nebulae (PPNe) are believed to represent a relatively short, intermediate evolutionary phase in the evolution of AGB stars to Planetary Nebulae (PNe). Our unbiased, high-resolution imaging surveys with HST of young PNe and PPNe show very strong morphological similarities between these classes, enabling us to extend our morphological scheme for PPN classification to young PNe, preserving virtually all of the primary and secondary descriptors, and adding a few new ones. These morphological surveys show that the primary shaping of PNe begins during the PPNe and/or late-AGB phase, and the key to understanding the shaping process lies in the study of these PNe progenitors. Here we present results from two recent studies of PNe progenitors: (i) Hα emission with very broad wings and P-Cygni profiles as probes of the region where the fast post-AGB outflows that do the shaping are most likely launched from, and (ii) equatorial waists with large-sized dust grains and large masses.

Keywords. Stars: AGB and post-AGB, stars: mass-loss, accretion disks, binaries: general

1. Introduction

The interaction of collimated (episodic) fast winds (CFWs) or jets, operating during the pre-planetary nebula (PPN) or very late-AGB phase, with the surrounding AGB circumstellar envelope, is most likely the primary mechanism whereby most planetary nebulae (PNe) acquire their aspherical shapes (Sahai & Trauger 1998). The formation of the dense waists seen in PNe likely occurs during the early PPN or late-AGB phase. Waists and lobes are perhaps formed nearly simultaneously, as suggested by Huggins (2007) from a study of a small sample, with waists forming a bit earlier (the expansion timescales are $\sim few \times 100$ to 1000 yr). We need to focus our attention on the PPN and very late-AGB phases if we are to succesfully resolve fundamental issues in the formation of aspherical PNe. These issues are (i) the origin and properties of the fast outflows ($\sim few \times 100\,\mathrm{km\ s^{-1}}$) which carry out the shaping, (ii) the origin and properties of equatorially-dense structures, i.e., the waists (bound/ expanding), (iii) the role of magnetic fields (e.g., in launching, accelerating and collimating outflows), and (iv) the role of binarity, which is widely believed to be the underlying cause (e.g., de Marco 2009), as it can induce stellar rotation and generate magnetic fields, lead to the formation of accretion disks, and result in common envelope ejection.

2. The Immediate Progenitors of Planetary Nebulae

We describe two studies from a multi-wavelength program (e.g., Sahai *et al.* 2007, 2008, 2010, 2011; Sánchez Contreras & Sahai 2011) of studying the early evolutionary phases – namely the PPN and late AGB phases – where the transformation to asphericity begins.

As part of this program, a systematic characterization of the observed morphologies of PPNe using HST imaging was presented by Sahai *et al.* (2007) using a scheme with 4 primary classes (B: bipolar, M: multipolar, E: elongated, and I: irregular), and a number of secondary descriptors, relating to, e.g., the presence of point-symmetry, ansae, halos, etc. We have now shown that this scheme can be adapted to the morphological classification of young PNe as well (Sahai, Morris & Villar 2011: SMV11), by adding 3 new primary classes – R (round), L (collimated lobe pair, but not pinched-in at the waist), and S (spiral arm), and additional secondary descriptors. Many of the latter are related to the central region: the differences in this region between PNe and PPNe may be explained as an evolutionary effect due to (i) the ionizing flux and (ii) hydrodynamic action of the fast radiative wind, from the PNe central star, on this region. In contrast, the morphologies seen during the nascent PPN phase, based on our HST imaging survey, are rather different, with compact ($\lesssim few \times 0.1''$), one-sided collimated structures being predominant, suggesting that the collimated-outflow phase has just begun (Sahai 2009, Sahai *et al.* 2010).

2.1. *Dusty Equatorial Waists/ Disks and Large Grains*

Dusty equatorial components are an important morphological feature of aspherical PPNe and PNe (SMV11). Observationally, there appear to be two manifestations of an equatorial dust component around pAGB stars, namely (1) as waists of bipolar/multipolar PPNe with sizes of about 1000 AU, and (2) as medium-sized ($\lesssim$ 50 AU) "circumbinary" disks in binary pAGB stars (hereafter dpAGB objects, i.e., disk-prominent pAGB objects) (e.g., van Winckel *et al.* 2009). The origin of these circumbinary disks and large dusty waists remains a mystery. Current models based on Bondi-Hoyle accretion from an AGB wind around a companion only produce small-sized ($\sim$1 AU), relatively low-mass accretion disks (Mastrodemos and Morris 1998), whereas common envelope ejection will likely result in significantly larger masses and overall expansion motion.

PPNe appear to be different in their morphologies, compared to the dpAGB objects, which generally appear to lack extended nebulae: except for HD44179 or 89 Her (Cohen *et al.* 2004, Bujarrabal *et al.* 2007), no extended nebulosity is seen optically, or in mm-wave continuum/CO emission – e.g., AC Her, U Mon, RV Tau are unresolved in our CARMA observations with sizes $< (1-2)''$ (Sahai *et al.* 2011). But the waist regions of PPNe share observational similarities with the disks in dpAGBs: both show (i) large submm excesses (de Ruyter *et al.* 2005, Sahai *et al.* 2006, Sánchez Contreras *et al.* 2007), which have been inferred to arise from large (mm-sized) grains, and (ii) crystalline silicate features (Gielen *et al.* 2008, Sahai *et al.* 2009). Both the mineralogy and grain sizes show that dust is highly processed, implying that the age of this component should be larger than that needed for such processing and grain growth ($\gtrsim$2000 yr; Jura, Webb & Kahane 2001). We thus need to probe the mass, kinematics and structure of the disk/waist regions in order to test formation models.

We have carried out a radio continuum survey (in X, Ka and Q bands, i.e., from 3.6 cm to 7 mm) with the EVLA in order to confirm the presence of very large dust grains in dusty disks and torii around the central stars in a sample of ten pAGB objects (Sahai *et al.* 2011). Supporting mm-wave observations were also obtained with CARMA towards three of our sources. Our EVLA survey resulted in a robust detection of our most prominent submm emission source, the PPN IRAS 22036+5306, in all three bands, and the dpAGB object, RV Tau, in one band. The observed fluxes are consistent with optically-thin free-free emission, and since they are insignificant compared to their submm/mm fluxes, we conclude that the latter must come from substantial masses of cool, large (mm-sized) grains. We find that the power-law emissivity in the cm-to-submm range for the large grains in IRAS22036 is ν^{β}, with $\beta = 1 - 1.3$. Furthermore, the value of β in the 3 to

0.85 mm range for the three dpAGB sources ($\beta \leqslant 0.4$) is significantly lower than that of IRAS22036, suggesting that the grains in dpAGB objects are likely larger than those in the dusty waists of PPNe. The sensitive upper limits to radio emission obtained for the remaining 8 objects in our study supports the idea that the physical mechanism predominantly responsible for the radio emission in pAGB objects is unrelated to that responsible for the mm/submm emission. We have estimated masses of the large grains (M_d) for 4 sources in our study for which the observed submm flux is known to come from a compact central source, and find that the values of M_d are significantly lower in the 3 dpAGB sources ($\sim 10^{-3} M_{\odot}$) compared to the PPN, IRAS22036 ($\sim 10^{-2} M_{\odot}$).

2.2. *Broad Hα emission from the Central Regions of PPNe*

There are no direct probes of the central regions of PPNe, from where the CFWs are presumably launched. Our optical spectroscopic survey of a sample of young PPNe (Sánchez Contreras *et al.* 2008) has revealed the widespread presence of very broad Hα emission, often with blue-shifted (P-Cygni type) absorption features. The Hα line-shape is most simply interpreted in terms of the following model – the broad emission profile arises from a compact central source; this emission (and stellar continuum) is scattered by dust in the walls of the nebular lobes, and the blue-shifted absorption is due to neutral or partially ionised outflowing gas in the lobes absorbing the scattered photons. Such a model has been successful in producing a detailed fit to the spatio-kinematic distribution of the blue-shifted absorption in the Hα line profiles observed with STIS/HST in the PPN Hen 3-1475 (Sánchez Contreras & Sahai 2001). Thus the broad Hα emission feature is a potential probe of the central region and we are carrying out similar STIS observations of a small sample of PPNe (GO 11634, PI: Sánchez Contreras) – *but we need to understand the mechanism which produces it.*

Such profiles had already been observed in young PNe, as well as symbiotic stars (e.g. Skopal 2006) and T Tauri stars (e.g, Edwards *et al.* 1987). Raman scattering of Lyβ, which leads to Hα with a width a factor 6.4 larger than the Lyβ width and a λ^{-2} wing profile, was proposed as the best mechanism to explain them (Arrieta & Torres-Peimbert 2003; ATP03). Other line-broadening mechanisms include electron scattering and emission from a rotating disk. Rotating disks around the central stars of young PNe which have masses in the range M=0.6-0.83$M_{\odot}$ and radii R=(1–18)$R_{\odot}$ produce velocities, $V_{max} < 400(M/R)^{1/2}$ km s^{-1} (ATP03), which are too low to directly account for the broad line-widths; PPN central stars are much cooler and therefore significantly larger, hence V_{max} is even lower. The extreme densities required for electron scattering (e.g., $n_e > 10^{12}$ cm^{-3} in M 2-9: ATP03) also make that an implausible mechanism.

We propose that the broad Hα wings arise as a result of Lyβ emission from a central ionized region, which is then Raman-scattered off the neutral CFW (the signature of the latter is the blue-shifted absorption feature in the Hα profiles). Our discovery of a radio continuum source in IRAS 22036 showing the presence of a dense, compact ionized region, suggests that the necessary condition for Raman scattering as the broadening mechanism - namely the availability of a relatively strong Lyβ flux – may be met in PPNe as a class. The mass-loss rate needed in the neutral outflow has to be substantial. Using the minimum scattering column density, $N_s = 10^{19}$ cm^{-2} required to achieve the Raman conversion efficiency needed to produce the very broad observed line-widths (see Fig. 1 of Lee & Hyung 2000), we find that $dM_s/dt = 0.9 \times 10^{-7} M_{\odot}$ yr$^{-1}(\theta/0.1'')$ (D/3 kpc) (V_{exp}/250 km s^{-1}) ($N_s/10^{19}$cm^{-2}), where θ is the size of the ionized region, and V_{exp} is the outflow velocity. Thus, for IRAS 22036, taking $\theta > 0.067''$ (derived from our EVLA study), D=2 kpc, $V_{exp} = 250$ km s^{-1}, we get $dM_s/dt > 6 \times 10^{-8} M_{\odot}$ yr^{-1}, a condition likely to be easily satisfied in this object.

Although we do not know the origin of such an ionized region in PPNe, a reasonable conjecture is that it is an ionized Keplerian disk around a compact (likely main-sequence) companion – in this case, the linewidth of Lyβ emission (due to Keplerian rotation) and the velocity of a CFW driven from such a region (comparable to the escape velocity) are about a few$\times$100 km s^{-1}, consistent with the observations.

3. Concluding Remarks

We are still far from understanding the mechanisms which produce aspherical PNe, and we need to focus our efforts as a community on PPNe and nascent PPNe, both observationally and theoretically. One of the least understood, but potentially most exciting clues of the launch site of the fast post-AGB outflows that do the shaping, is the broad-wing Hα emission which we find in PPNe. Observational surveys of Hα in PPNe and young PN with class-E and R morphologies, as well as in nascent PPN, will be helpful in understanding its origin. High angular resolution ($< 0.3''$) interferometric mapping (e.g., in the submm with ALMA) of the large-grain emission will help in understanding the origin of equatorial waists in these objects, and radio continuum observations at cm wavelengths with the EVLA will help in constraining the physical properties of central ionized regions.

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