RevMexAA (Serie de Conferencias), **15**, 17–19 (2003)

MULTIPOLAR BUBBLES, POINT-SYMMETRY, AND JETS IN DYING STARS

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RESUMEN

Las imágenes con resolución angular y rango dinámico sin precedente de las nebulosas planetarias jóvenes y protoplanetarias (NPJ y NPP) tomadas con el *Telescopio Espacial Hubble* (*HST*) nos han mostrado que casi todos estos objetos son altamente asféricos con morfologías multipolares complejas. La complejidad, organización y simetría de las estructuras morfológicas ha llevado a cabo cambios radicales en nuestro entendimiento de los procesos de pérdida de masa durante la evolución estelar tardía. Por lo tanto, hemos propuesto que los flujos colimados de alta velocidad o los chorros que operan durante la fase evolutiva del AGB (rama asintótica de las gigantes) tardía y/o post-AGB juegan un papel fundamental en formar las nebulosas planetarias. En este trabajo presentamos nuevos resultados de nuestro programa a multifrecuencias de imágenes y espectroscopía de NPJ y NPP que apoyan este modelo. También describimos un esfuerzo paralelo de inferir las propiedades de los flujos rápidos mediante simulaciones numéricas.

ABSTRACT

The imaging of young planetary and pre-planetary nebulae (YPNe and PPNe) with unprecedented high angular resolution and dynamic range using the *Hubble Space Telescope* (*HST*), has shown that most of these objects are highly aspherical, with complex multipolar morphologies. The complexity, organization and symmetry of the morphological structures has radically changed our understanding of the mass-loss processes during late stellar evolution. We have proposed that high-speed collimated outflows or jets operating during the late AGB and/or early post-AGB evolutionary phase play a fundamental role in shaping PNe. We present here new results from our multi-wavelength program of imaging and spectroscopy of YPNe and PPNe that support this model, and describe a parallel effort to infer the properties of the fast outflows using numerical simulations.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: POST-MAIN SEQUENCE — STARS: MASS LOSS**

1. INTRODUCTION

How do the slowly expanding (5 to 15 $\mathrm{km\,s^{-1}}$), largely spherical, circumstellar envelopes (CSEs) of AGB stars (Neri et al. 1998) transform themselves into highly aspherical PNs with fast outflows ($\gtrsim$ 100 $\mathrm{km\,s^{-1}}$) along one or more axes (e.g., Balick & Frank 2002; Sahai & Trauger 1998)? *Hubble Space Telescope* (*HST*) imaging of young PNe (YPNe; Sahai & Trauger 1998) and PPNe (e.g., Ueta, Meixner, & Bobrowsky 2000; Kwok, Hrivnak, & Su 2000; Sahai et al. 1998, 1999a,b) has shown the widespread presence of diverse aspherical morphologies in these objects. Although *axisymmetric* (elliptical and bipolar) shapes can be produced by the Generalised Interacting Stellar Winds model, in which a fast, radiatively-driven, isotropic post-AGB stellar wind is hydrodynamically collimated by an equatorially dense AGB CSE (Balick & Frank 2002), the morphological data indicate that the fast winds in PPNe/YPNe are born collimated, i.e., collimated as they are launched (Sahai 2001), and millimeter-wave CO data indicate that these winds are not radiatively driven (Bujarrabal et al. 2001). Sahai & Trauger (1998) have proposed that such self-collimated fast winds (CFWs) are the primary mechanism for the dramatic change in circumstellar geometry and kinematics as stars evolve off the AGB.

2. HIGH-RESOLUTION OBSERVATIONS OF PPNE/YPNE

HST imaging shows a complex and diverse variety of morphologies in PPNe/YPNe (see e.g., Kastner, Soker, & Rappaport 2000). The six examples in Figure 1 highlight multipolar and/or point-symmetric nebulae—objects in which aspherical structures (bubbles/shells/lobes/disks) with different symmetry axes are present. While objects like

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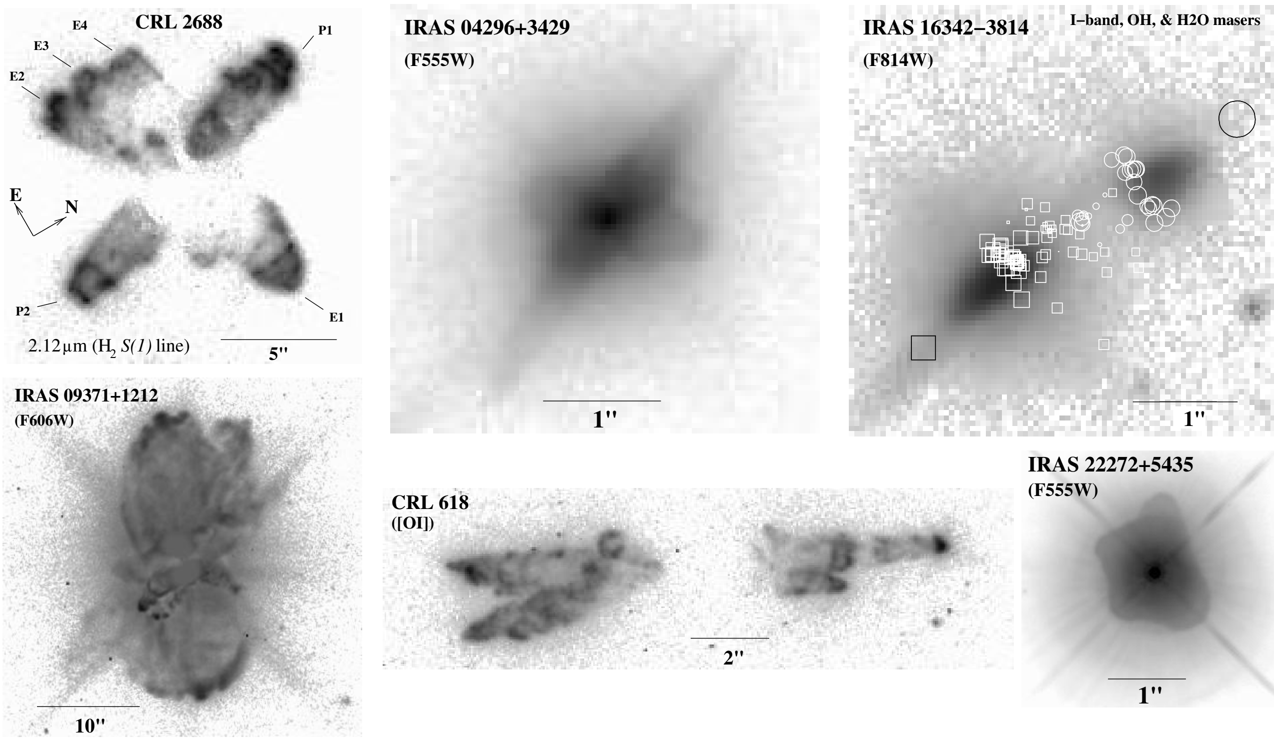

Fig. 1. *HST*/WFPC2 images (in reverse grayscale) of selected pre-planetary and young planetary nebulae with multipolar or point-symmetric morphologies. In CRL 2688, the extended outer regions of the nebula, which represent the spherical envelope due to AGB mass loss, are not shown.

Hen 3-1475, with a high degree of point-symmetry, suggest the operation of a precessing jet, other objects with multiple, elongated lobes of roughly similar extent, e.g., He 2-47 and M 1-37 (Sahai 2000) and CRL 618 (Sánchez Contreras, Sahai, & de Paz 2002), indicate the simultaneous operation of multiple outflows with differing axes. The bipolar PPN IRAS 04296+3429 shows a truncated, central disk which is not orthogonal to its collimated bipolar lobes (Sahai 1999). PPNe like CRL 2688 and IRAS 09371+1212 show secondary low-latitude collimated lobes in addition to the primary polar lobes, suggesting the operation of low-latitude jets (Sahai et al. 1998, 2000)—interferometric imaging of CO $J = 2$–1 emission in CRL 2688 (Cox et al. 2000) confirms this interpretation.

Although *HST* imaging continues to play a major role in influencing our thinking on the shaping of PNe, the need for kinematical data with angular resolution comparable to *HST*'s (vital for testing theoretical models) is growing. We have therefore begun two programs: (1) interferometric mapping of OH/ H_2O maser emission in order to trace the kinematics of the structures discovered in PPNe nebulae with *HST*, and (2) *HST*/STIS long-slit spectroscopy of selected PPNe and YPNe. In program 1, we have studied the kinematics of 3 young bipolar PPNe, Roberts 22 (Sahai et al. 1999a), IRAS 16342-3814 (Sahai et al. 1999b), and IRAS 22036+5306 (Sahai et al. 2003) using their OH maser emission. Amongst these, IRAS 16342-3814, arguably the least evolved of these PPNe, is notable for the exceptionally high speed of its molecular outflow traced in 22 GHz H_2O maser emission (Likkel & Morris 1988; also Morris, Sahai, & Claussen 2003). In program 2, we (i) discovered an ultra-fast ($\sim 2300\,\mathrm{km\,s^{-1}}$) "pristine" outflow (in absorption) in the point-symmetric bipolar PPN Hen 3-1475 (Sánchez Contreras & Sahai 2001); the outflow appears to be collimated quite close to the central star, and (ii) have imaged shocked-gas emission from a high-velocity ($350i/45^\circ\,\mathrm{km\,s^{-1}}$) directed, knotty outflow within $85\,\mathrm{AU}(d/0.5\,\mathrm{kpc})$ of the center in the carbon-rich AGB object, V Hya (Figure 2)—spatially resolving its fast outflow for the first time.

A major obstacle to our understanding of the CFWs in PPNe/YPNe is that, with a few exceptions (e.g., Hen 2-90, Sahai & Nyman 2000), the CFWs interact quite strongly with the surrounding dense AGB CSE, and manifest themselves only *indirectly*

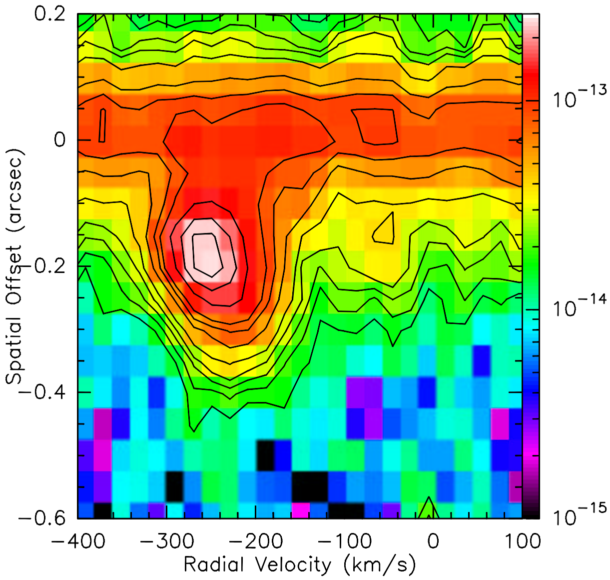

Fig. 2. Long-slit (STIS/*HST*) spectrum of [S II] λ4069.7 emission in the carbon-rich AGB object V Hya showing a knotty, high-velocity outflow. Contours are (0.15, 0.2, 0.25, 0.3, 0.4, 0.6, 0.8, 1, 1.5, 2.2, 5) $\times 10^{-15}$ erg s^{-1} cm^{-2} arcsec^{-2}.

as the elongated lobes of swept-up circumstellar material which they produce. We have therefore begun a modeling effort to *infer* the properties of the CFWs by fitting the lobe shapes and emission properties in specific objects using hydrodynamical simulations (Lee & Sahai 2003)—e.g., we find that the W1 lobe in CRL 618 requires an ongoing, pulsed, $\sim 300\,\mathrm{km\,s^{-1}}$ wind with an opening angle of $\sim 10°$ and mass flux of $2.5 \times 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$.

The nature of the launching mechanism for the CFWs remains frustratingly elusive, although several models have been proposed. A bipolar jet from a precessing/wobbling accretion disk may produce point-symmetric shapes, but multipolar shapes, as, e.g., in CRL 618, might require a second paradigm. In the years to come, the search for the launching mechanism will clearly remain an important stimulus for the study of PPNe and YPNe.

R. S. and M. M. have been partially supported for this work through a NASA LTSA grant (No. 399-20-61-00-00); R. S. has also been funded by NASA/STScI GO grants 09100.01-A, 09101.01-A, and 09102.01-A.

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