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BIPOLAR AND MULTIPOLAR JETS IN PROTOPLANETARY AND PLANETARY NEBULAE

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RESUMEN

Uno de los retos más emocionantes con que actualmente se enfrentan las teorías de evolución posterior a la secuencia principal, es entender cómo estrellas AGB (ingl. "Asymptotic Giant Branch") y sus envolturas cicunestelares esféricas (siglas en inglés: CSEs) se transforman en nebulosas planetarias (NPs) con su asombrosa variedad de morfologías asféricas. El modelo más exitoso para dar forma a los NPs—el modelo generalizado de vientos estelares interactuantes, en el cual un viento esférico de alta velocidad ($> 1000\ km\ s^{-1}$) interactua con un CSE AGB denso en el ecuador para producir una NP *axisimétrica*—ahora parece inadecuado como resultado de nuevos datos del Telescopio Espacial Hubble (*Hubble Space Telescope, HST*).

Este artículo presenta nuevas imágenes obtenidas con HST de nebulosas planetarias y proto-planetarias con flujos colimados. A menudo los flujos parecen ser de naturaleza *multipolar*, indicando cambios episódicos del eje bipolar del flujo colimado o la operación de flujos colimados múltiples con diferentes orientaciones. En particular, el descubrimiento casual de chorros extendidos altamente colimados en la nebulosa planetaria Hen 2-90 y sus sorprendentes similitudes morfológicas a los YSO (siglas en inglés para objetos estelares jóvenes) de baja masa es fuerte evidencia para un mecanismo físico común para los flujos colimados en proto-estrellas y estrellas evolucionadas. Resumimos brevemente las hipótesis teóricas actuales que llevan a un mejor entendimiento de la naturaleza y origen de estos flujos.

ABSTRACT

One of the most exciting challenges facing theories of post-main sequence evolution today is to understand how Asymptotic Giant Branch (AGB) stars and their round circumstellar envelopes (CSEs) transform themselves into planetary nebulae (PNe) with their dazzling variety of aspherical morphologies. The most succesful model for shaping PNe—the "generalised interacting-stellar-winds" model, in which a fast (> 1000 km s^{-1}) spherical stellar wind interacts with an equatorially-dense AGB CSE to produce an *axisymmetric* PN—now appears inadequate as a result of new data from the *Hubble Space Telescope* (*HST*).

This paper presents new HST images of proto-planetary and planetary nebulae with collimated outflows. The outflows appear to be quite often *multipolar* in nature, indicating episodic changes in the axis of a bipolar jet-like outflow or the operation of multiple collimated outflows with different orientations. In particular, our serendipitous discovery of a very highly-collimated, extended jet in the planetary nebula Hen 2-90 and its amazing morphological similarity to low-mass YSOs is the strongest evidence yet for a common physical mechanism for collimated outflows in protostars and evolved stars. We briefly summarise current theoretical hypotheses which may lead to a better understanding of the nature and origin of these outflows.

Key Words: **CIRCUMSTELLAR MATTER — ISM: JETS AND OUTFLOWS — PLANETARY NEBULAE — STARS: AGB AND POST-AGB — STARS: MASS-LOSS**

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1. INTRODUCTION

Collimated jets are one of the most intriguing, yet poorly understood phenomena in astrophysics. Evidence for the presence of jets has been found for a wide variety of object classes, which include active galactic nuclei (these proceedings) and a slew of stellar objects, which include young stellar objects (YSOs: see Bally & Reipurth, these proceedings), massive X-ray binaries (e.g., SS433: Margon 1984), black hole X-ray transient sources (e.g., Mirabel & Rodríguez 1999), symbiotic stars (e.g., R Aqr: Burgarella & Paresce 1992), supersoft X-ray sources (e.g., Southwell, Livio, & Pringle 1997), and finally, as we show in this paper, planetary and proto-planetary nebulae (PNe & PPNe).

Stellar evolution from the Asymptotic Giant Branch (AGB) towards the planetary nebula stage is poorly understood in spite of extensive study. The drastic change of the circumstellar structure and kinematics—from spherical, slowly expanding AGB envelopes (e.g., Sahai & Bieging 1993; Neri et al. 1998) to bipolar or multipolar PNe with high polar velocities—is particularly puzzling. The Generalized Interacting Stellar Winds (GISW) model can produce a wide variety of *axisymmetric* PNe shapes through the expansion of a fast ($\gtrsim$ 1000 km s^{-1}) stellar wind inside a slowly expanding mass-loss envelope (of the progenitor AGB star) possessing an equatorial density enhancement (Balick 1987), as verified by detailed hydrodynamical modeling (e.g., Frank & Mellema 1994). However, the GISW model has been unable to satisfactorily address a number of issues. Two of the most important ones are (i) the nature and origin of the asymmetry in the AGB envelopes, (ii) the presence of "quadrupolar" structures (e.g., Corradi & Schwarz 1995; Manchado, Stanghellini, & Guerrero 1996), ansae and point-symmetric structures.

In order to decipher the physical mechanisms responsible for shaping planetary nebulae, we need to focus our attention on *young PNe* and *PPNe*, which are most likely to retain strong signatures of the physical phenomena crucial to their development. But these young objects are *compact*, and important structural details are usually blurred beyond recognition in ground-based optical images. The stable PSF and high angular resolution of the *Hubble Space Telescope* (*HST*) allows one to image reflection or emission-line nebulosities with very high dynamic range, making *HST* the facility of choice for studying PPNe and young PNe.

2. *HST* OBSERVATIONS

We summarise below our *HST* imaging surveys (using the Wide Field & Planetary Camera 2: WFPC2) of a large number of young PNe (Sahai & Trauger 1998: ST98, Sahai 2000a) and detailed studies of individual PPNe. Although these studies are in progress, the data obtained so far provide important clues to the processes which shape PNe.

2.1. *Detailed Studies of Protoplanetary Nebulae*

We have carried out detailed studies of several PPNe by imaging their reflection nebulosities—in these objects, the central star (with spectral types K,G,F,A) is not yet hot enough to substantially ionize the circumstellar matter. PPNe imaged by us include (1) CRL 2688 or Egg Nebula (Fig. 1 and Sahai et al. 1998a,b); (2) IRAS 16342-3814 (Fig. 1), Hen 3-401 (Fig. 1), and Roberts 22 (Sahai et al. 1999a,b,c); (3) IRAS 04296+3429 (Sahai 1999); and (4) IRAS 09371+1212 or Frosty Leo Nebula (Fig. 1 and Sahai et al. 2000). Those imaged by other groups include IRAS 17150-3224 (Kwok et al. 1998), IRAS 16594-4656 and 17245-3951 (Hrivnak et al. 1999), and IRAS 22272+5435, 17423-1755, & 06530-0213 (Ueta, Meixner, & Bobrowsky 2000). All show bipolar or multipolar morphologies. In particular, the best-resolved of these, CRL 2688 (Sahai et al. 1998a; Cox et al. 2000) and Frosty Leo (Fig. 1), show directly the presence of multiple low-latitude jet-like outflows. CRL 2688 is also a prime example of a small list of PPNe and PNe which show the presence of roughly concentric arcs in their extended halos—evidence for a quasi-periodic modulation of the AGB mass-loss rate on time-scales of a few hundred years. Analysis of archival long-slit observations of the PPN He3-1475 (e.g., Riera et al. 1995), taken with the Space Telescope Imaging Spectrograph (STIS), have led to the discovery of a "pristine" ultra-fast post-AGB outflow (with speeds up to 2300 km s^{-1}), which is highly collimated (length/width $\gtrsim$ 7) close to the central star ($\sim 10^{16}$ cm) along a direction different from previous mass-ejection axes in this object, and with a radially increasing velocity (Sánchez-Contreras & Sahai 2001).

2.2. *Imaging Surveys of Young Planetary Nebulae*

An imaging survey of a sample of young PNe, inspired by the class of very-low-excitation objects discovered in an objective prism emission-line survey by Sanduleak & Stephenson (1972, 1973) is in progress. This sample has been uniformly selected on the basis of excitation criteria, and represents an *unbiased* sample for determining the morphological characteristics of young PNe (details in ST98). Three of the brightest PNe which meet our selection criteria—BD +30°3639 (Harrington et al. 1997), MyCn 18 (Sahai et al. 1999d), and M 1-92 (Bujarrabal et al. 1998)—have been studied in detail using *HST*.

The most notable conclusions from our *HST* observations are:

1. There are no round PNe or PPNe; most objects are *multipolar*.
2. The variety of morphologies seen is much larger than known from ground-based surveys.
3. Point-symmetry is widely manifest.
4. Many PNe have internal geometric components (e.g., rings, inner hourglass).
5. The central star is often offset from the centers of these components.
6. Faint round halos are found around the central aspherical nebula in many PNe and PPNe, (evidence for isotropic mass-loss on the AGB)

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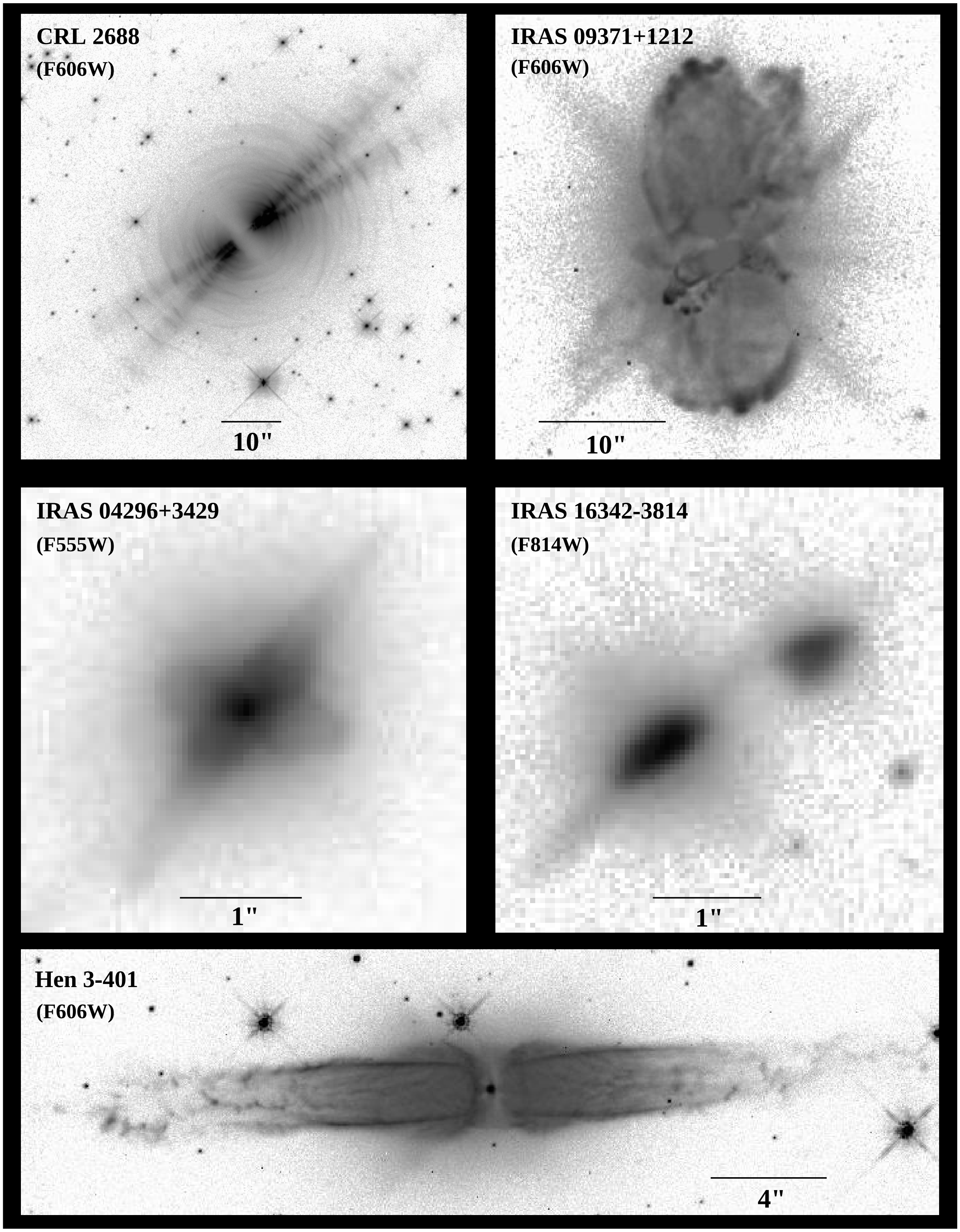

Fig. 1. *HST*/WFPC2 images (in reverse grey-scale) of selected proto-planetary nebulae. Sharp features have been modestly emphasized in IRAS 09371+1212 (Frosty Leo Nebula) and Hen 3-401 as described in ST98). Note the wide variety of morphologies; the concentric arcs and "searchlight beams" in CRL 2688 (details in Sahai et al. 1998a) and the collimated jet-like lobes near the nebular waist in IRAS 09371+1212 (details in Sahai et al. 2000).

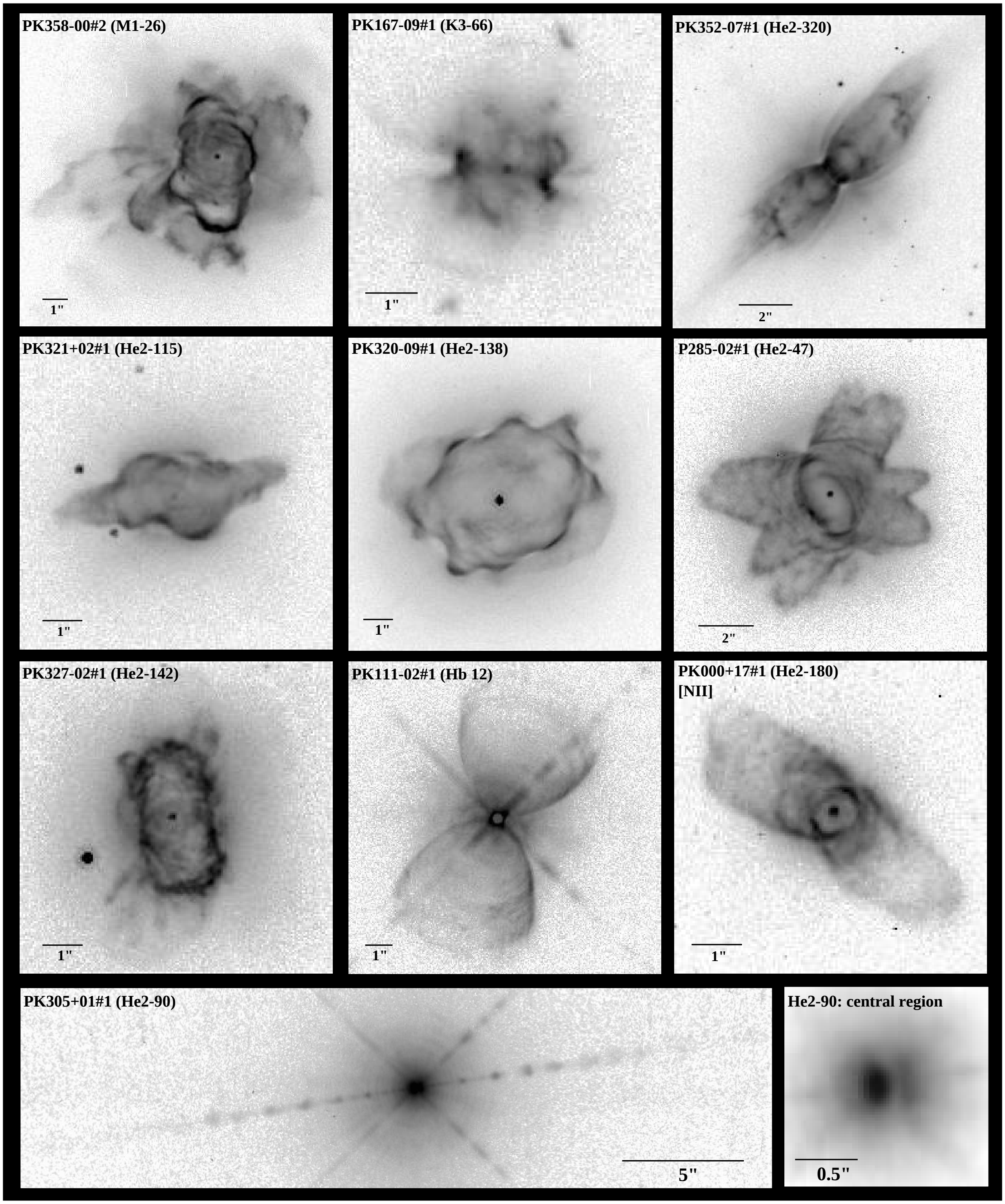

Fig. 2. *HST*/WFPC2 Hα images (in reverse grey-scale) of young planetary nebulae from our survey. Note (a) the wide variety of morphologies, including the plethora of lobes in He 2-47 (details in Sahai 2000b), and (b) the amazing morphological similarity of the highly-collimated, pulsed, bipolar jet and central bipolar nebula with obscuring edge-on disk seen in Hen 2-90 to the features seen in low-mass YSOs like HH30 (details in Sahai & Nyman 2000). Sharp features have been emphasized as described in ST98 (the spikes at $\pm 45°$ in the HB 12 & He2-90 images are telescope artifacts).

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7. Multiple concentric rings are found in the halo in several objects (evidence for episodic changes in the AGB mass-loss rate).

Thus, although our *HST* images show that PPNe/PNe shapes are characterised by *complex symmetries* they are not *chaotic*. In addition, subtle but crucial features of the geometrical shapes are revealed for the first time, specially the presence of "corners" and "parallelogram" shapes. Thus, many objects, whose bright shells have been classified as "elliptical" from the ground are actually (point-symmetric) parallelograms (e.g., IC 418, Sahai 2000b, and NGC 7027, Latter et al. 2000). Finally, our *HST* survey has led to the serendipitous discovery of a very highly-collimated, pulsed, bipolar jet in the PN Hen 2-90 (Fig. 2) (Sahai & Nyman 2000). The amazing morphological similarity of Hen 2-90 to a low-mass YSO provides strong empirical evidence for a common physical mechanism for generating collimated outflows in protostars and evolved stars.

3. A NEW MODEL FOR PRODUCING ASPHERICAL PLANETARY NEBULAE

Our *HST* images of young PNe strongly suggest that the key to understanding the shaping of aspherical PNe is a physical mechanism which can generate multipolar and point-symmetric structures. Long-slit spectroscopic imaging of several bright PNe shows that point-symmetric features in the images are also kinematically point-symmetric (e.g., Guerrero, Vázquez, & López 1999). Bipolar rotating episodic jets (BRETs) have been invoked for creating point-symmetric structures in individual PNe (López, Meaburn & Palmer 1993).

We (ST98) propose a two-step mechanism in which, first, a high-speed ($\gtrsim$ few $\times$ 100 km s^{-1}) collimated or jet-like outflow (or outflows) operating during the late-AGB or early post-AGB evolutionary phase carve an imprint within an intrinsically spherical AGB mass-loss envelope. This imprint *sets the stage* for the development of an aspherical planetary nebula. Subsequent expansion of a hot, tenuous, even faster stellar wind inside this imprinted AGB envelope, then produces the observed PN, whose shape and structure depends in detail on how the characteristics (direction, strength, opening angle) of the jet-like outflows change with time. Extended dense equatorial structures, if present, also provide an impediment to the expansion of the fast wind in the equatorial plane. However, all of our PNe show complex aspherical shapes, regardless of whether or not such structures are visible in the images, which suggests that the equatorial structures are not the primary agent for producing aspherical PNe. Departures from point-symmetric structure can result in two ways: (1) departure from bipolar symmetry in the jets (which in the extreme would result in a one-sided jet), and (2) departures from symmetry in the progenitor AGB envelope. Such departures could lead to irregularly shaped nebular structures, which are also observed.

3.1. *Properties of Jets in PPNe and PNe*

We now summarise the main properties of jets in PPNe and PNe, as inferred from our *HST* studies:

1. In most cases, jets are not seen directly, but indirectly (due to the presence of dense ambient circumstellar material with which the jet interacts); however such evidence is quite compelling, and includes (a) collimated, often limb-brightened, elongated lobes and (b) diametrically-opposed ansae.

2. Jets occur in both polar directions and at low-latitudes (e.g., in PPNe CRL2688, Frosty Leo, Roberts 22).

3. Bow-shock shaped substructures within lobes indicate temporal variations in outflow speed and/or mass-loss rate.

4. The speed of material associated with jets is at least few$\times$100 km s^{-1}, and can be as high as $\sim$2000 km s^{-1} (e.g., He3-1475).

5. Either the jets are bipolar and change direction episodically or multiple jets operate quasi-simultaneously.

Detailed, extensive modelling of jets interacting with the circumstellar envelopes of the progenitor AGB stars are needed to derive intrinsic jet properties (e.g., speed, mass-loss rate, opening angle, collimation and their temporal variations).

3.2. *Mechanisms for Making Wobbling Jet-like Outflows*

Mechanisms for producing jet-like outflows, directly or indirectly, require the presence of a close binary companion. The most promising ones are those in which the outflows are (i) accretion disk-driven (e.g., Morris 1987; Soker 1996; Soker & Livio 1994), or (ii) magneto-hydrodynamically (MHD) collimated by a stellar toroidal magnetic field (e.g., García-Segura 1997; Różyczka & Franco 1996). In case (i), the jet-axis may change due to a radiation-induced instability which can warp the accretion disk, causing it to precess or wobble (Livio & Pringle 1997), whereas in case (ii), precession of the rotation axis of the star due to a binary companion can change the direction of the outflow. In addition, in the absence of strong hydrodynamical interaction, the observed velocity gradient in the ultra-fast wind can be attributed to acceleration. The radially increasing outflow velocity in the ultra-fast "pristine" jet in He3-1475 provides support for the MHD model (Sánchez-Contreras & Sahai 2001). The variety and complexity of the structures seen in our sample of young PNe suggest that the changes in the properties of these outflows are episodic, and sometimes frequent. This appears difficult to achieve in a simple binary system. We suggest that the changes in the properties of these jets, and possibly their production, may be related to the presence of multiple sub-stellar companions (such as brown dwarfs and giant Jupiters). The recent detections of Jupiter-mass companions around Sun-like stars (e.g., Marcy 1998), specially those in close orbits (orbital radius < 0.2 AU) (e.g., Butler et al. 1997) should spur new theoretical efforts to investigate the affects of such bodies on the formation and shaping of PNe.

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