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COLLIMATED OUTFLOWS IN PLANETARY NEBULAE

J. A. López

Instituto de Astronomía, Universidad Nacional Autónoma de México

RESUMEN

Nuestro entendimiento sobre la formación de nebulosas planetarias (PNe) ha sido profundamente influenciado en años recientes por la detección de flujos colimados de alta velocidad en estos objetos. Flujos que alcanzan velocidades de expansión de varios cientos de km s^{-1} así como evidencias de eyecciones múltiples y episódicas, desde la etapa de proto-PNe, han modificado radicalmente nuestros conceptos previos sobre la evolución de objetos post-AGB. Los modelos hidrodinámicos por si solos parecen ahora insuficientes para reproducir muchos de estos fenómenos dinámicos detectados. Modelos MHD y la influencia de núcleos binarios han incrementado su importancia en la interpretación de la diversidad de flujos colimados en PNe. Este trabajo presenta una semblanza de estos fenómenos, y se discute algunos de los retos actuales y tendencias en el campo.

ABSTRACT

Our understanding of the formation of planetary nebulae (PNe) has been profoundly influenced in recent years by the detection of high-velocity, collimated outflows in these objects. Outflows reaching expansion velocities of several hundred km s^{-1} and evidences of episodic, multiple ejection events since the proto-PNe stage, have radically modified our previous concepts of the evolution of post-AGB objects. Hydrodynamic models alone seem now incapable of reproducing many of the attendant dynamical phenomena observed in PNe. MHD models and binary nuclei are thus playing an increasingly important role in interpreting the diversity of collimated outflows in PNe. This paper presents an overview of these phenomena and discusses some of the current challenges and trends in the field.

Key Words: **HYDRODYNAMICS — ISM: JETS AND OUTFLOWS — PLANETARY NEBULAE: GENERAL**

1. INTRODUCTION

The concept of collimated outflows in PNe is not new. The presence of elliptical and bipolar morphologies in PNe, both implying different degrees of collimation of the stellar wind, has been known since the early studies of these objects (e.g., Curtis 1918). Morphological classifications of PNe always include the three basic shapes: round, elliptical and bipolar, i.e., these classifications mainly reflect the varying degrees of collimation, as observed in ground-based images, of the main nebular shells of PNe. As the quantity and quality of the observations increased, individual authors added particular sub-classes in each category, with differences mainly arising from the characteristics of the sample available to them at the time (cf. Khromov & Kohoutek 1968; Gurzadyan 1969; Balick 1987; Schwarz, Corradi, & Stanghellini 1992; Manchado et al. 1996).

However, since the early 1990's, mounting observational evidences have led to an increasing awareness of the importance and complexity of symmetric collimated structures in PNe (e.g., Miranda & Solf 1992; López, Meaburn, & Palmer 1993; Schwartz 1993; Balick et al. 1993; and see the review by López 1997). The *Hubble Space Telescope* (*HST*) has now resolved, and confirmed, many planetary nebulae that reveal a diversity of point-symmetric structures and multiple, collimated outflow directions, some of them with jet-like characteristics, among other fascinating and perplexing features. Incidentally, none of these structures had been anticipated to exist in PNe by the theory. This is a good example of what Don Cox has expressed in his summary for this conference: "*Almost nothing we know of in the universe was predicted before being seen...*". The more we have been able to observe the real structure of PNe the more puzzling we find them. The database now provided by the *HST* clearly indicates the need for a reformulation of current theories to explain the origin and evolution of PNe. Models containing a blend of new concepts and revitalized theories, such as MHD and binary nuclei, are therefore now being vigorously pursued.

The number of relevant papers published during the last 10 years in the subject is too numerous to cite and one would surely make unfair omissions if such an attempt was made. It is not intended here to make a review in that sense. The intention of this work is rather only to point out some of the key problems in our current attempts to understand how planetary nebulae are formed and to exemplify the current challenges the field meets with some recent observational work. Some of the *HST* images presented here have been drawn from the recent compilation (http://aries.usno.navy.mil/ad/pne) made by Terzian & Hajian (2000), individual credits for each image are given in the legends to the figures.

2. BASIC IDEAS

The basic general concept of a planetary nebula is that of an evolved, intermediate mass star whose outer layers have been expelled in the AGB phase via a slow and dense wind at a high mass-loss rate. The star then moves towards higher effective temperatures and the characteristics of the mass-loss process change. The central star becomes the source of a fast and tenuous, isotropic wind. This fast wind eventually catches up with the previously ejected, slower moving material; the interaction produces a momentum exchange between both winds and hydrodynamic discontinuities form. An outward shock compresses, heats and accelerates the slow-moving and ambient materials whereas an inward facing shock decelerates, heats and compresses the stellar wind. At the boundary between these inner and outer shocks a contact discontinuity is formed. A combination of photoionization and thermal equilibrium calculations plus this hydrodynamic model of interacting winds (e.g., Dyson & de Vries 1972; Kwok, Purton, & Fitzgerald 1978) satisfactorily represents the main physics of spherical bubbles. In the cases of elliptical and bipolar nebulae, the presence of an aspherical density distribution, in the form of a dense toroidal cloud, is incorporated in the models before the fast wind is switched on. By modifying the properties of this equatorial density enhancement (EDE) the main observed features in axisymmetric PNe are successfully reproduced (e.g., Kahn & West 1985; Mellema, Eulderinck, & Icke 1991; and see the recent comprehensive review by Frank 1999).

3. THE ORIGIN OF BIPOLARITY

The presence of equatorial density enhancements in PNe is not an artifact of the models. Dense toroidal structures at the center of axisymmetric nebulae are indeed observed in ionized (see Fig. 1*a*) and molecular forms (e.g., Huggins et al. 1996). These toroidal structures are an integral and pervasive part of the PNe formation process, even some simple-looking ring nebulae have been shown to be bipolars seen pole-on (e.g., Bryce, Balick, & Meaburn 1994; Guerrero, Manchado, & Serra-Ricat 1996). However, why and how an aspherical density distribution develops in the late AGB phase is still not known. During the AGB phase mass is lost predominantly in an isotropic way. Even in some cases where clear signs of early bipolar development are apparent, the underlying halo is seen to be composed of concentric spherical shells (e.g., Sahai et al. 1998; Kwok, Su, & Hrivnak 1998; and see Figs. 1*b* and 1*f*) that must originate in the previous mass-loss episode, during the AGB stage. Calvet & Peimbert (1983) have suggested that since bipolar nebulae evolve from massive progenitors ($> 2.4\ M_{\odot}$), which are observed to have high rotation velocities in the main sequence (v sin $i \approx 100 - 200$ km s^{-1}), at the time they reach the AGB phase the star releases mass with high angular momentum developing a pancake-like shape. Another alternative is close binary evolution that undergoes a common envelope phase during the AGB (e.g., Iben & Livio 1993). In this case, if the secondary gets contained within the primary's extended envelope when the latter reaches its largest dimensions, dynamical drag will steal orbital momentum from the secondary which will be gained as angular momentum by the primary's envelope. A spiraling-in process ensues and the envelope, or part of it, may be ejected as a consequence. This material could thus at a later time be identified as the equatorial density enhancement.

A further alternative could be the early disruption of very low-mass companions, such as brown dwarfs or giant planets, during the spiraling-in process. The remains of this disruption may amount up to a hundredth

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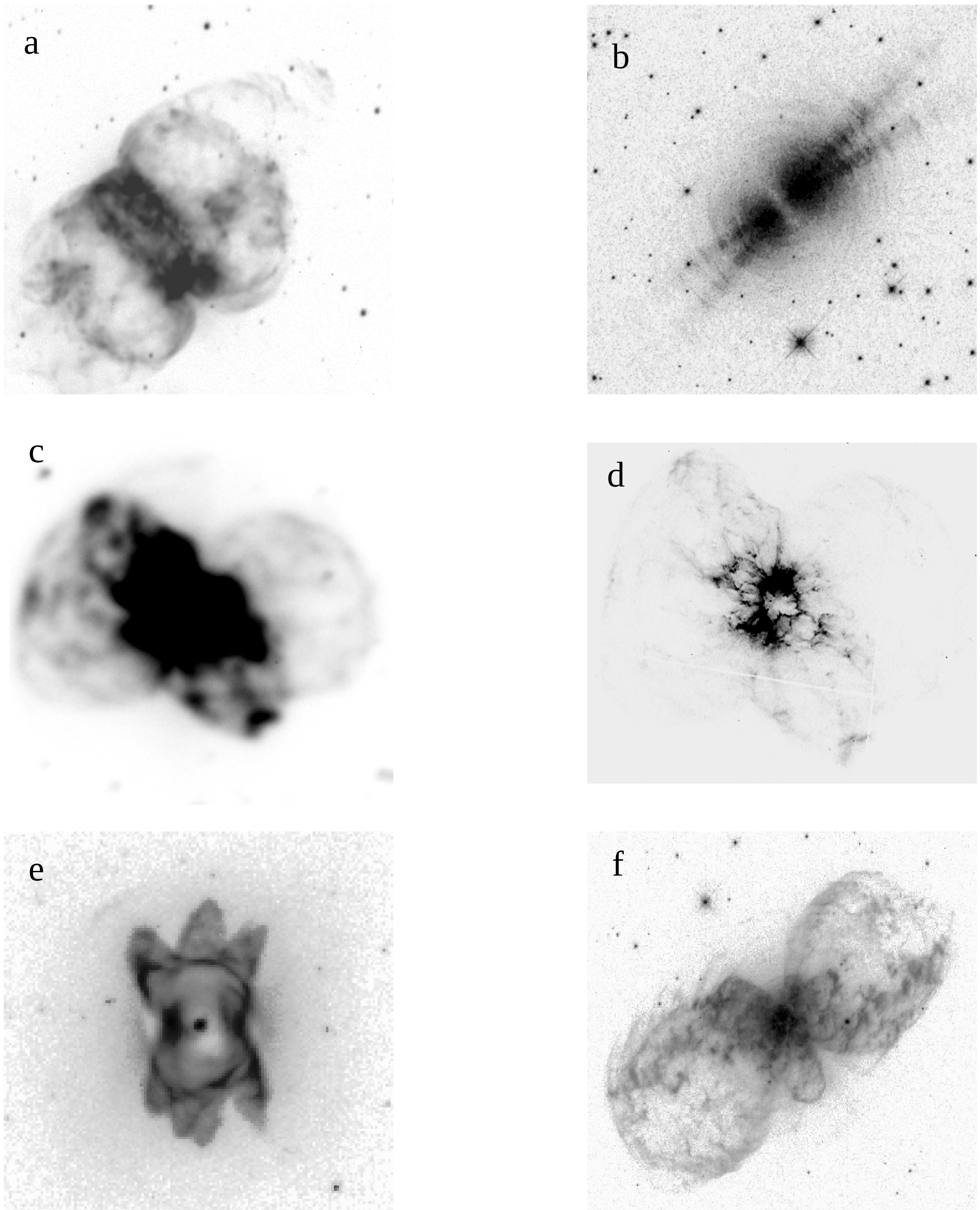

Fig. 1. Bipolarity and poly-polarity in PNe. The presence of equatorial density enhancements (EDE) is a key ingredient in the formation of bipolar nebulae. The mechanisms that form EDE are still unknown. Bipolarity develops from the early stages of PN formation (see text). *(a)* NGC 650 a typical bipolar nebula with a conspicuous EDE. *(b)* The proto-PN CRL 2688 already showing clear signs of bipolarity and concentric shells. *(c)* NGC 2440 a poly-polar nebula with more than one pair of opposing lobes. *(d)* NGC 2440 (*HST*), the inner regions and secondary lobes revealed. *(e)* He 2–339 (*HST*), a young poly-polar nebula. *(f)* Hb 5 (*HST*), a bipolar nebula with a point-symmetric structure along the inner borders of its opposing lobes. Credits for the images: *(a)* López (and see Bryce et al. 1994) *(b)* Sahai & Trauger and WFPC2 Scence Team. *(c)* López *(d)* Westphal, and see López et al. (1998) *(e)* Sahai & Trauger *(f)* Balick, Icke, & Mellema.

of a solar mass and stay orbiting, distributed as a disk or belt around the primary (Reyes-Ruiz, private communication). These are all interesting ideas needing further investigation. However, to date, we still await the key observations that may give us the definite clues as to the origin of the equatorial density enhancements in axisymmetric PNe. To understand this process becomes even more relevant when we try to understand the poly-polar nebulae and more complex outflows.

4. POLY-POLARITY, EPISODIC EJECTIONS AND HYPERSONIC JETS

Poly-polar nebulae are those PNe containing more than a single pair of opposite lobes. A typical example is NGC 2440 (López et al. 1998; see Fig. 1*c*). The main bipolar structure lies nearly E-W at PA 85°; in addition, two other bipolar structures emerge at PA's 60° and 35°, respectively. The general impression is that of an episodic, rotating, bipolar outflow. The filamentary lobes at PA 60° appear to be the latest rotated outflow that originally may have also generated the PA 35° lobes (see Fig. 1*d*). In this case the plane of the central toroid seems orthogonal to the PA 60° outflows and clearly off-axis with respect to the largest bipolar structure at PA 85° . Similar signs of poly-polarity have been now found by the *HST* in very young and compact PNe, such as He 2–339 (Sahai & Trauger 1998; and see Fig. 1*e*).

Another peculiar characteristic of some bipolar nebulae is the formation of point-symmetric shapes along the inner borders of their opposing lobes. An example of this class of objects is Hb 5 (see Fig. 1*f*). One possible interpretion for the formation of these structures is to consider the action of a rotating or precessing, collimated outflow that is switched-on after the bipolar nebula has been formed (e.g., Cliffe et al. 1995). Alternatively, García-Segura & López (2000) consider an MHD model where this effect is reproduced by considering a steady misalignment of the magnetic collimation axis with respect to the symmetry axis of the bipolar wind outflow, the latter defined perpendicular to the equatorial density enhancement.

Evidence of episodic ejections, rotation (or precession) and higher collimation conditions and outflow speeds than those described above are also found in a number of objects. Bipolar, rotating, episodic jets, or BRETs (López et al. 1995) are appreciated in objects such as Fleming 1 (López et al. 1993; see Fig. 2*a*), and He 3–1475 (Borkowski, Blondin, & Harrington 1997; see Fig. 2*b*). The latter showing ouflow velocities in excess of 800 km s^{-1} ! (Riera et al. 1995; Harrington 2000). Another object with hypersonic ouflow velocities is the Hourglass Nebula MyCn 18 (see Fig. 2*c*) where opposite strings of knots have been ejected at velocities in excess of 500 km s^{-1} (Bryce et al. 1997; O'Connor et al. 2000). The line profiles in these knots are very narrow, suggesting no interaction with the ambient medium and on both sides with velocities increasing nearly linearly with distance from the core. This odd kinematic behaviour has been recently reproduced by García-Segura et al. (1999) via magnetized winds. Hypersonic velocities in MyCn 18 are not its only remarkable property; *HST* imagery of its core (Sahai et al. 1999) has revealed a second and smaller ring surrounding the central star interior to the apparent EDE that is observed in the large scale image of this nebula. Yet another interesting example in the class is found in the PNe Hb 4 (see Fig. 2*d*) where the highly collimated outflows reach radial velocities of $\pm$ 200 km s^{-1} with respect to the systemic. Steffen & López (1998) have modeled high resolution line profiles of Hb 4 as a developing episodic, two-sided jet and noted that the jets are not orthogonal to the plane of the central annular structure.

5. THE ORIGIN OF JETS IN PNE

The presence of jets in PNe presents a dilemma, since the driving agents for two-sided jets are generally thought to be embedded in accretion disks and the latter were not supposed to be established components in PNe.

How are jets formed in PNe? Hydrodynamical models meet certain difficulties in this regard since fast winds do not tend to converge into stable structures in the PNe environment (e.g., Dwarkadas & Balick 1998).

Magnetized winds from rotating stars have been shown to be a potentially efficient channel to produce jets in PNe (e.g., Różyczka & Franco 1996; García-Segura et al. 1999). A drawback in MHD models is the lack of information on stellar rotation velocities of the PNe cores and their magnetic field strength. Therefore, some assumptions on these key parameters are required. Nevertheless, MHD models have proven to be one of the most promising avenues for advancement in the understanding of the structural development of PNe (see García-Segura et al. in these proceedings).

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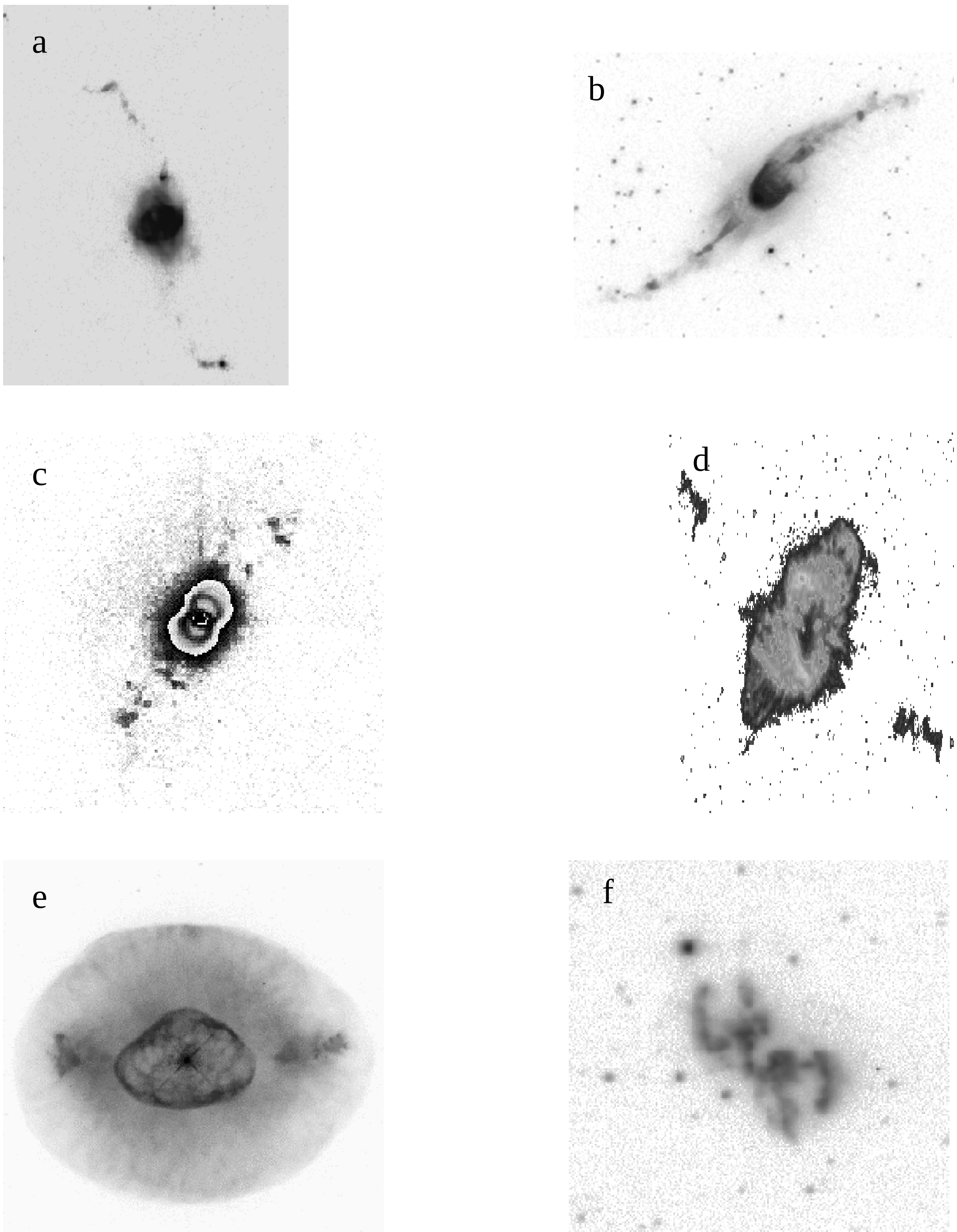

Fig. 2. The diversity of high-velocity, collimated outflows in PNe (see text). *(a)* Fleming 1, the proto-type of a bipolar, rotating, episodic jet or BRET. *(b)* He 3–1475 (*HST*), this young PNe has expansion velocities reaching 800 km s^{-1}. *(c)* MyCn 18, the external knots on either side of the Hourglass Nebula reach velocities in excess of 500 km s^{-1}. *(d)* Hb 4 (*HST*), outflowing collimated strings move at 200 km s^{-1}. *(e)* NGC 6826 (*HST*), a typical example of a PNe with FLIERS. *(f)* Pe 1–17, an extreme case of point-symmetry in PNe. Credits for the images: *(a)* López *(b)* Borkowski, Harrington, & Bobrowsky *(c)* O'Connor et al. 2000 *(d)* Harrington & Bobrowsky *(e)* Balick et al. (1998) *(f)* Manchado et al. (1996) and see Guerrero, Vázquez, & López (1999).

Close binary systems that undergo a common envelope phase may eventually result in the formation of an accretion disk (e.g., Soker & Livio 1994). Reyes-Ruiz & López (1999) have shown that an accretion disk may be formed around the PN nucleus only when Roche lobe overflow occurs from a low-mass secondary ($M_2 < 0.08\ M_\odot$) at orbital separations $< 2\ R_\odot$. In these cases a geometrically thin accretion disk is formed as the companion disintegrates in a dynamically unstable mass-transfer process. Significant accretion rates ($> 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$) are found to last only a few thousand years, i.e., jets through this process can only be formed during a relatively brief period at the exit of the AGB phase. This is consistent with the fact that 'active' jets in PNe are observed in the early stages of PNe formation. Of course, magnetic fields or some other mechanism are still required to launch the jets. There is, however, a crude state of knowledge of the physical processes at various points of this model and additional intensive numerical modeling is still required. Even so, this mechanism is considered a fundamental one that can significantly influence AGB and post-AGB evolution.

6. FLIERS AND POINT-SYMMETRIC PNE

Another class of intriguing outflows are those generally observed as symmetric pairs of knots or 'tails' expanding with respect to the nucleus at velocities of the order of $30 - 50\ \mathrm{km\ s}^{-1}$. These curious features have been intensively investigated in the past by Balick and collaborators and a description of their main properties as fast, low ionization, emission regions or FLIERS is given in Balick et al. (1998). FLIERS were originally found associated with some elliptical PNe (see Fig. 2*e*), although they have now been identified in many other types of PNe (e.g., Corradi et al. 1996). A consistent explanation of their origin has remained elusive. Several types of models have been explored for the formation of these structures, such as ionization fronts on localized dense knots and bow shocks of fast knots ramming through the nebular shell. Dopita (1997) has discussed FLIERS in terms of the effects of shocks in the strongly radiative PN medium. Alternatively, Redman & Dyson (1999) have presented a model in which FLIERS represent recombination fronts in mass-loaded jets. Recently, Steffen & López (2000) have presented a new model where FLIERS are formed in the stagnation zone of partially collimated stellar winds. A concave bow-shock structure is formed due to the lack of momentum flow along the axis of a mildly bipolar stellar wind and the stagnation knots are formed when the shocked environment medium accumulates at the apex of the outer shell and is compressed to a dense knot. This model is able to account for many of the characteristics of FLIERS and circumvents some problems encountered earlier with collimation mechanisms. However, the definition of FLIERS, which originally was well bounded, has been used in recent times to encompass nearly any [N II] bright knot found in the periphery of PNe shells, traveling either with nearly null or very high radial velocity. In these conditions a single model can hardly account for all the properties observed, since symmetric ejecta, shocks, recombination fronts or simply dynamical instabilities that may form in the nebular rim, developing dense, low ionization knots and expanding with it, are not always being distinguished.

An outstanding characteristic in nearly all types of collimated outflows in PNe is symmetry, not only bipolar or plane symmetry, but point-symmetry. There are only twelve PNe formally classified in catalogues as point-symmetric (Schwarz et al. 1993; Manchado et al. 1996). However, Guerrero, Vázquez, & López (1999) have pointed out that a certain degree of point-symmetry spans nearly all the morphological groups and evolutionary stages in PNe. This must be considered an important clue to the mass-loss mechanisms during the PN formation process and on the ability of the nebular structure to retain the signatures of point-symmetry at later times. A particularly dramatic example of a point-symmetric PNe is Pe 1–17, shown in Figure 2*e*. The beautiful images delivered by the *Hubble Space Telescope* in recent years, have only enhanced the wide variety of PNe and proto-PNe with point-symmetric structures.

7. A MULTIPLE PN

In addition to the diversity and complexity of collimated outflows in PNe described above, a final note is now devoted to a singularly unusual case, the PN KjPn 8. This is an extreme poly-polar nebula whose large-scale structure is characterized by a giant, biconical envelope ($14' \times 4'$) oriented at PA 72° and with an age of $1 - 2 \times 10^4$ years (see Fig. 3). The kinematics of this giant bipolar structure has been studied by López et al. (1997) and its dynamics and peculiar structure have been modeled by Steffen & López (1998) as the result of the action of an episodic, collimated, bipolar outflow impinging on the surrounding environment.

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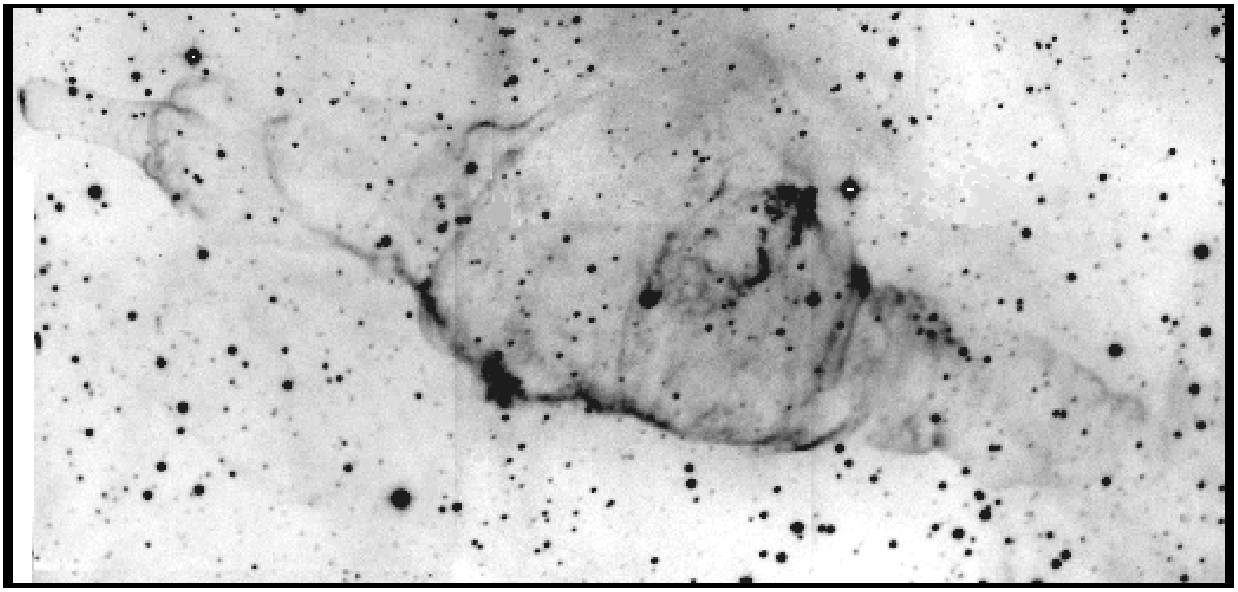

Fig. 3. A deep Hα wide field, ground-based image of the polypolar nebula KjPn 8. The whole nebula is $14' \times 4'$ in extent. The main symmetry axis of the large biconical envelope lies at PA 72°. Secondary and younger high-velocity, bipolar outflows are oriented at PA 126°. The nebular core, located at the geometric center of the nebula has been resolved by the *HST* as a very young, ionized ring whose axis is aligned with the high velocity outflows. Disks of CO and H_2 (not shown here) are directly associated with the ionized nebular ring and all share the same orientation. This molecular material indicates a second episode of heavy mass-loss. The simultaneous presence of an old bipolar structure and a very young core with a compact bipolar jet system have been interpreted by López et al. (2000) as two distinct PNe events, probably arising from a binary system and separated by $\approx 10^4$ years.

The nebular core is only $\sim 4''$ in diameter and its physical conditions indicate a low excitation (young) nebula with ionic abundaces corresponding to extreme type I PNe (Vázquez, Kingsburgh, & López 1998). The core is surrounded by a massive, optically thick disk of CO $J = 1-0$, $30''$ in diameter (Huggins et al. 1997; Forveille et al. 1998). Furthermore, a ring of excited H_2, $8''$ in diameter (López et al. 1999) is contained within the CO structure. Recent WFPC2/*HST* images of the nebular core (López et al. 2000) have now revealed the inner ionized ring expanding at only 16 km s^{-1} around the central star. The dynamical age of the nebular core is thus estimated in only $\lesssim 1.2 \times 10^3$ years. The CO, H_2 and ionized rings all share the same orientation and their axis is aligned with a pair of high-velocity (~ 320 km s^{-1}) collimated outflows oriented at PA 126°. The kinematical age for these outflows is estimated at ≤ 3400 yr as given directly by their angular displacements from the nebular core combined with measurements of their expansion proper motions (Meaburn 1997).

The strikingly different position angles between the bipolar flows in KjPn 8 indicate the occurrence of abrupt changes in outflow directions and substantial differences in times between ejection events. The associated CO and H_2 molecular material must be related to a second heavy mass-loss episode prior to the formation of the ionized nebular core and indicates that the formation of the giant bipolar envelope had its origin in a different event, unrelated to the creation of the present nebular core and associated high-velocity, bipolar outflows. The simultaneous presence of an old, evolved bipolar structure and a much younger nebular core and bipolar jet system has led López et al. (2000) to propose that we may be here witnessing two PNe-type events having been consecutively produced from a binary core, on each occasion developing bipolar outflows with different orientations. These characteristics indicate that KjPn 8 may be the first known multiple planetary nebula that has been detected.

8. FINAL REMARKS

Planetary nebulae have been known and studied for about a century. Major advances in their understanding came with the application of atomic theory to the analysis of their spectra during the first half of this century. Thus, PNe became one of the first astrophysical plasmas to be studied, apart from the Sun. After all these years of studying PNe, many important aspects of them are now well understood. However, as we approach the next millenium, the field has been invigorated by a wealth of new observational material that has in many ways transformed the standard concepts on their formation and structural evolution. Theory is quickly trying to catch-up with the new ideas emerging from the analysis of high-quality data. There is no doubt that PNe will continue to be an exciting field of research in the coming century.

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J. A. López: Instituto de Astronomía, UNAM, Unidad Ensenada, Apartado Postal 877, Ensenada, B. C., 22800, México (jal@astrosen.unam.mx).