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WINDS, BUBBLES, AND OUTFLOWS IN PLANETARY NEBULAE

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RESUMEN

El propósito de este trabajo es resaltar las contribuciones que John Dyson ha hecho al estudio del medio interestelar en general y en particular al campo de las nebulosas planetarias. Adicionalmente, hago una revisión de algunos problemas actuales en relación a la formación y evolución de flujos en expansión en nebulosas planetarias.

ABSTRACT

The aim of this work is to highlight the contributions that John Dyson has made to the study of the interstellar medium in general and, in particular, to the field of planetary nebulae. I review a few outstanding problems regarding the formation and evolution of outflows in planetary nebulae.

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

1. INTRODUCTION

The scientific contributions of John Dyson to astronomy, and in particular to the study of the interstellar medium, have made an unquestionable impact in our present-day view of the field. He has covered nearly every relevant aspect of the interaction of stellar and galactic winds with the interstellar medium. Dynamics and kinematics of circumstellar and interstellar material have been extensively studied by him. The early evolution of H II regions and wind-blown bubbles, active galactic nuclei, supernovae remnants and planetary nebulae are all among his hunting trophies.

His pioneering works (e.g., Dyson 1968, 1975) on the consequences of clumpy and inhomogeneous media in circumstellar and interstellar environments and mass-loaded flows, have become of particular relevance in recent years with the advent of high-resolution imaging, as provided by the *Hubble Space Telescope*, which has highlighted the importance of considering these phenomena to properly explain the physical processes that occur in the interaction of stellar winds with the surrounding neutral, molecular or ionized material.

Planetary nebulae (PNe) are among the objects where the interaction of the stellar wind and ionizing radiation from the central star with a non-homogeneous, gaseous and dusty environment provide the conditions to clearly reveal the complex nature of these phenomena. Here I briefly review a few of the latest advances in our understanding of how PNe evolve and discuss some of the current outstanding problems, particularly related to those areas where John Dyson has made contributions in this field.

2. EARLY EVOLUTION OF PNE

In the classical view of a PN this is described, to a first approximation, as a wind-blown bubble. The basic concept is that an evolved, low-mass star leaves the AGB phase after expelling its outer layers via a slow and dense wind at a high mass-loss rate. As the core reaches higher effective temperatures the characteristics of the mass-loss process change, gradually turning into a fast and tenuous isotropic wind. This fast wind eventually overruns the previously ejected, slower moving material, producing a momentum exchange between both winds and forming hydrodynamic discontinuities.

The dynamical effects of injecting isotropic, supersonic gas into a relatively stationary medium, thereby producing a 2–shock flow pattern, were examined by Pikelner (1968) and Dyson & de Vries (1972) while studying the dynamical consequences of mass loss from early-type stars on a surrounding nebula. Kwok, Purton, & Fitzgerald (1978) introduced the interacting winds, 2–shock model into the PN realm to account for the global dynamics of a spherical planetary nebula. Isotropic winds, spherical symmetry and homogeneous media were part of these early models, that nevertheless give a very fair representation of the basic physics involved in these processes.

3. CLUMPY PLANETARY NEBULAE

Most nearby planetary nebulae do not show a smooth density distribution when observed at high spatial resolution. Clumps of material are apparent and ubiquitous in the nebular shell. The *Hubble Space Telescope* has provided us with a large number of examples, such as the Helix, the Eskimo, NGC 6751, and IC 4406, just to name a few (see Figure 1). The clumps have cold molecular cores (Huggins et al. 2002) that seem to account for their apparent longevity. Their estimated masses range from 10^{-4} to $10^{-5}\,M_{\odot}$. The clumps show narrow line widths (Meaburn et al. 1998). The fragmented, clumpy structure of the nebular shell has important dynamic consequences for its subsequent development. However, the origin of these clumps is still unclear. They may be formed by dynamical instabilities near the ionization front in accelerating shells driven by stellar winds (Capriotti 1973; Breitschwerdt & Kahn 1990) or, as suggested by Hartquist & Dyson (1997), these may also be formed in the envelope of AGB stars by the Parker instability behind shocks in the pulsating atmospheres of these stars. However, recent observations by Huggins & Mauron (2002) of NGC 7027 and IRC+10216 do not support the latter. Alternatively, they suggest that clump formation may occur as the neutral, circumstellar shell is fragmented at the transition phase by directed outflows. Along a somewhat similar line, Steffen & López (2003) have presented hydrodynamic models of a supersonic stellar wind interacting with a thick, toroidal distribution of high-density clouds. The supersonic wind percolates through the cloud ensemble producing a range of cometary structures in the contact discontinuity. Ablation and mass-loading processes become relevant factors in the evolution of the cometary tails.

4. MASS-LOADED FLOWS IN CLUMPY MEDIA

The interaction of clumps and tenuous, fast flows and stellar radiation produces tails or cometary shapes, as observed in the Helix nebula (e.g., O'Dell & Handron 1996). The stellar radiation and wind combine to produce an erosive effect on the surface of the clump, thus the clump loses mass, which is carried away by the wind and modifies its dynamic properties. For example, electron temperature deviation in the halo of some PNe, such as NGC 6543, have been explained as flows of mass-loaded wind percolating from the inner regions of the nebula and shocking clumps in the halo, producing local electron temperature enhancements (Meaburn et al. 1991; Dyson 1992; Arthur, Dyson, & Hartquist 1994).

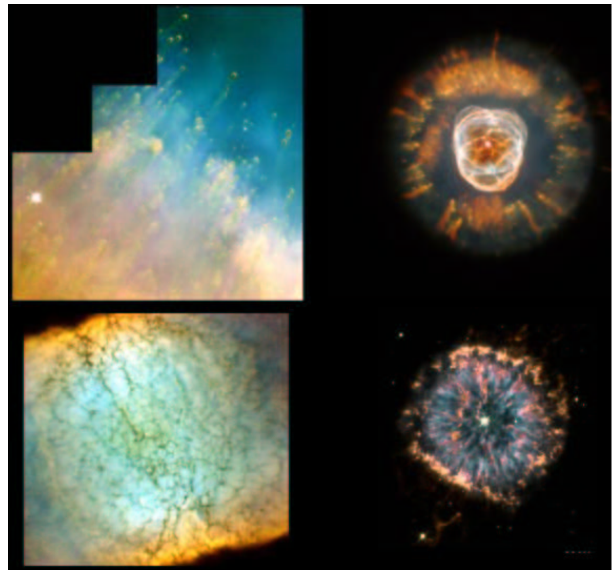

Fig. 1. Examples of the clumpy structure in the nebular shell of PNe are provided by the cases shown in this mosaic. The objects are: top left—the Helix nebula; top right—the Eskimo nebula; bottom right—NGC 6751; bottom left—IC 4406. All images have been obtained from the *Hubble Space Telescope* web page, credits: NASA, STScI and the *Hubble* Heritage Team.

Mass-loaded flows have also been invoked to explain fast, low ionization, emission regions, or FLIERS, (e.g., Balick et al. 1998). Redman & Dyson (1999) have studied FLIERS in terms of mass-loaded, supersonic, collimated outflows that form stationary recombination fronts as neutral clumps within the outflow are ablated and incorporate mass into the flow. As mass is added, the flow slows down, increasing the density and absorbing photons to form the recombination front. Typical velocities, densities and ionization structures can be accounted for in these models. Mass-loaded flows have also been deemed responsible for the velocity spikes observed to emerge from the knots surrounding the hydrogen-deficient PN Abell 30 as manifestations of a mass-loaded wind after ablation of the surrounding dense clumps (Meaburn & López 1996).

5. COLLIMATED OUTFLOWS IN PNE

One of the most startling findings on the dynamics of PNe in recent times has been the discovery of bipolar, high-speed jets in these objects (e.g., López 2000; López 2003). These collimated outflows bear striking resemblances, in some cases, with those observed in young stellar objects (YSOs; see Figure 2). Furthermore, they show a pervasive (almost perverse) tendency towards point-symmetry

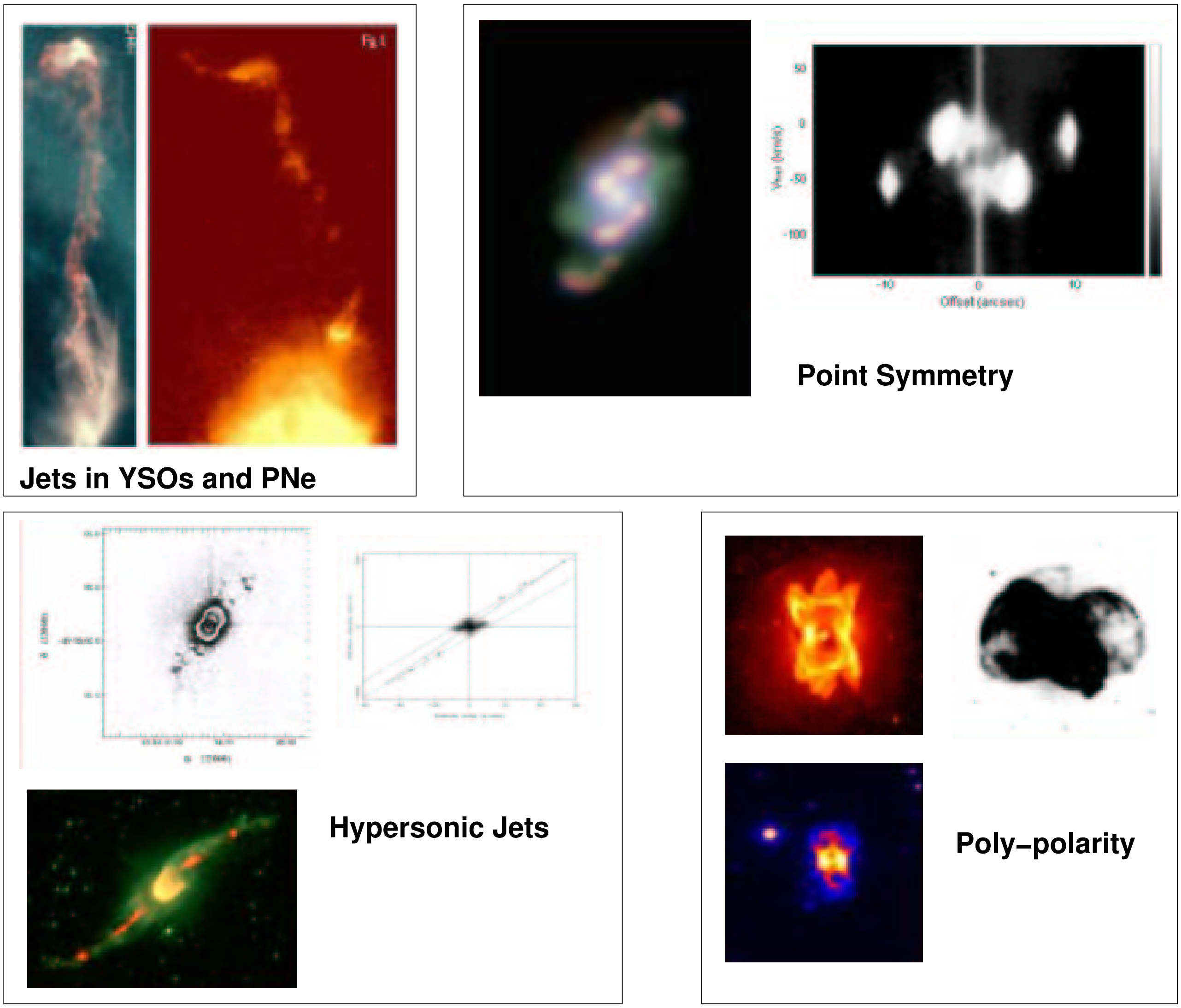

Fig. 2. Diverse examples of collimated outflows in PNe. Top left: the similarity between jets in YSO's and PNe is exemplified by these images of HH 47 (image credit: NASA and STScI and Burrows, Hester, & Morse) and the northern jet of Fleming 1 (López, Meaburn, & Palmer 1993). Top right: the point-symmetric structure of collimated outflows in PNe is clearly revealed by the case of IC 4634 where this characteristic is also seen replicated in velocity space, as shown by the line profile to the right of the image. (Images and spectra, Toledano & López 2003.) Bottom left: examples of hypersonic outflows, ranging from 500 to 1200 $\mathrm{km\,s^{-1}}$, are represented here by the cases of MyCn 18 (Bryce et al. 1997; O'Connor et al. 2000) and He 3-1475 (Borkowski & Harrington 2001). Finally, (bottom right) polypolarity is represented here with the cases of He 2-239 (Sahai & Trauger 1998), NGC 2440 (López et al. 1998) and NGC 7026.

that gives them in many cases the appearance of emerging from a rotating or precessing source in episodic events, though this may be in some cases a misleading impression (see García-Segura & López 2000). Polipolarity, i.e., the simultaneous presence of two or more pairs of bipolar, collimated outflows, adds complexity to the puzzle of how an evolved star may be able to produce these outflows (e.g., Sahai & Trauger 1998). A proto-typical example of this class is NGC 2440 (López et al. 1998). There are cases where hypersonic outflows, reaching expansion velocities well in excess of 500 $\mathrm{km\,s^{-1}}$, have been unambiguously detected (see the review by López 2003).

Answers to these questions have been sought in recent times beyond pure hydrodynamic arguments, turning attention to the effects of binary cores (e.g., Soker & Rappaport 2000; Mastrodemos & Morris 1998; Reyes-Ruíz & López 1999) and magne-

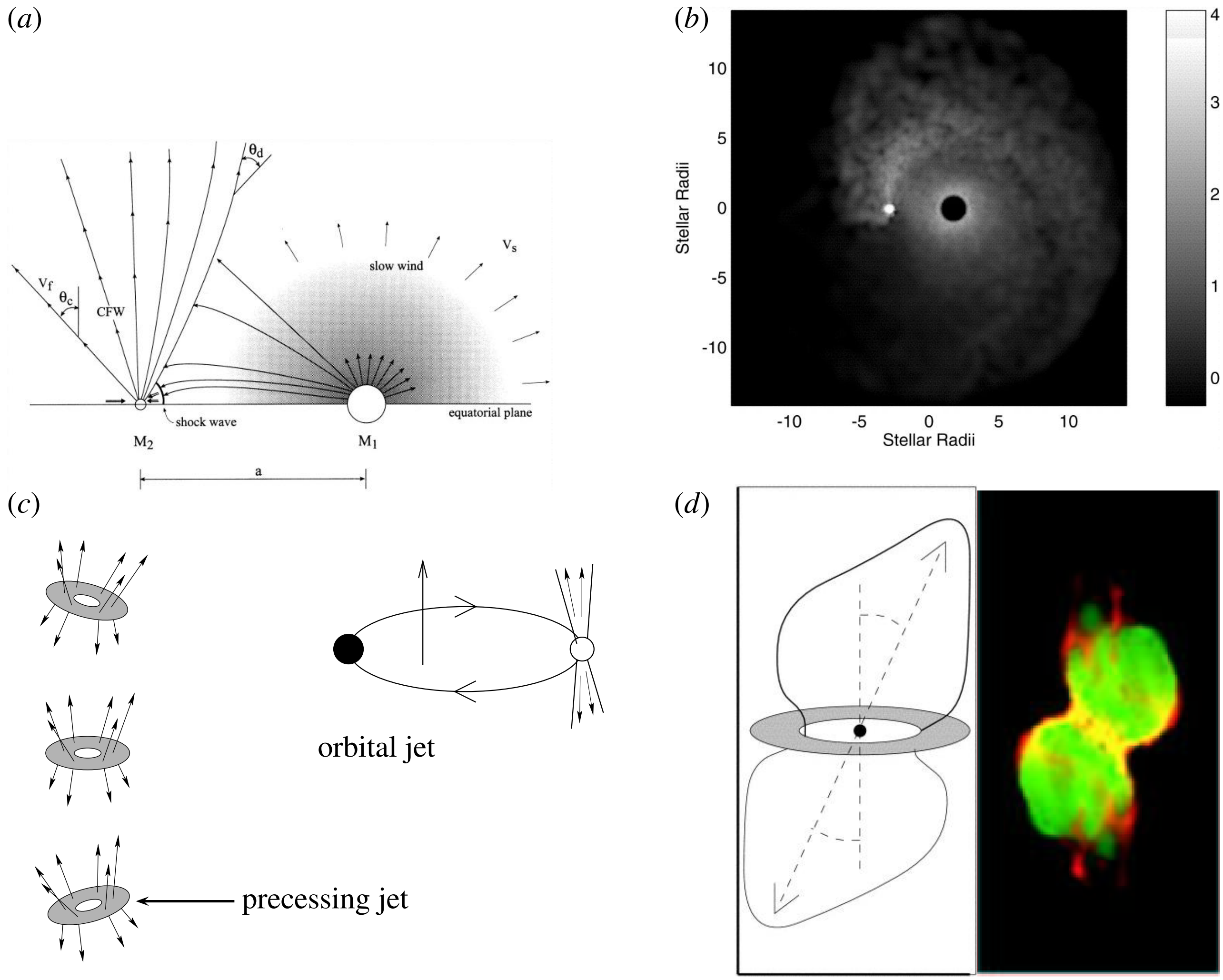

Fig. 3. The complexity of collimated outflows has been recently modeled invoking binary cores and magnetized winds. (*a*) A model from Soker & Rappaport (2000) on the effects of wind accretion from a white dwarf onto a main sequence star. (*b*) Same as before but with SPH numerical modeling of the wind accretion process, from Mastrodemos & Morris (1998). (*c*) Sketch from López (2003) on the consequences of rotation and precession from a source with a collimated outflow. (*d*) MHD modeling of a magnetized, collimated wind that is tilted with respect to the major axis (García-Segura & López 2000).

tized winds (Różyczka & Franco 1996; García-Segura 2003; Gardiner et al. 2000; see Figure 3).

6. FINAL REMARKS

We now know that collimated outflows are formed in the first stages of development of a PN, just as it is leaving the AGB. This is also the time when clump formation in the ejected shell must develop. Finding how these two phenomena influence each other is one of the current major challenges in the dynamics of PNe.

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