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JETS AND JET-LIKE STRUCTURES OF LOW-IONIZATION IN PLANETARY NEBULAE

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RESUMEN

Se discuten los resultados de un programa encaminado a estudiar las propiedades físicas, origen y evolución de las "estructuras de pequeña escala y baja ionización en PNs". Clasificamos y discutimos, de acuerdo a los posibles mecanismos de formación, las propiedades de una muestra de más de 50 PNs recopiladas de la literatura. Además de esto, hemos obtenido datos morfológicos y cinemáticos de 10 de estas PNs, encontrando estructuras de baja ionización muy distintas unas de otras, tanto en cuanto a las velocidades de expansión, como a las formas, tamaños y posición respecto de las componentes nebulares principales. Está claro que hay que considerar diferentes procesos físicos para explicar la formación de las diversas estructuras observadas. Mostramos aquí ciertos resultados ilustrativos de nuestro trabajo—referentes a IC 4593, NGC 3918 y NGC 6337—y planteamos algunas de las cuestiones que queremos investigar. El resultado más interesante que obtenemos es que las LIS colimadas tienen velocidades de expansión que aumentan linealmente desde las regiones internas a las externas. Esto es una restricción importante para los modelos, siendo, de hecho, una de las predicciones de los modelos de vientos interactuantes para la formación de *jets* cuando se tienen en cuenta campos magnéticos.

ABSTRACT

In this contribution we discuss new results of a program aimed at studying the physical properties, origin and evolution of "low-ionization, small-scale structures in PNe". Within this project we classify and discuss the properties of a sample of more than 50 PNe, collected from the literature, in the light of their possible formation mechanisms. In addition, we obtained images and spectra for 10 of these PNe, finding low-ionization structures with very different properties relative to each other, in terms of expansion velocities, shapes, sizes and locations relative to the main nebular components. Several physical processes have to be invoked in order to account for the formation and evolution of jets and jet-like structures observed. We present here some results which are illustrative of our work—on IC 4593, NGC 3918, NGC 6337—comparing the different low-ionization structures in these PNe and illustrating some of the questions that we try to address. The most interesting result we obtained is that the collimated LIS present a linear increase in the expansion velocity from inner to outer regions. This is an important constraint on the models and is, in fact, one of the predictions of the interacting-stellar-wind models for the formation of jets, if stellar magnetic fields are considered.

Key Words: **ISM: JETS AND OUTFLOWS — PLANETARY NEBULAE: INDIVIDUAL (IC 4593, NGC 3918, NGC 6337)**

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1. INTRODUCTION

The most accepted scenario for the formation of a planetary nebula (PN) is the one in which the PN shell is a result of the interaction between a slow AGB wind and a fast post-AGB wind, in such a way that the latter acts as a snow plow and sweeps up matter in the AGB wind into a high-density shell. Such models are called interacting-stellar-winds models (ISW models), and are successful in predicting the observed properties (density, velocity, mass) of spherical and non-spherical PNe (Kwok, Purton, & FitzGerald 1978; Kwok 1994). Observationally, the shell dominates the optical emission, but the emission from the halo (AGB remnant) is also present, both being main components of the PNe. These main structures are better identified in the Hα and [O III] emission. On the other hand, the structures we are interested in are those selected by being more prominent in low-ionization lines, like [N II] and [S II], fainter in Hα, and almost absent in [O III]. These are called low-ionization structures (LIS).

There exist some families of models that try to explain the origin of the LIS. Basically, these are: interacting stellar wind models (Frank, Balick, & Livio 1996; Dwarkadas & Balick 1998; García-Segura et al. 1999); jet interaction with the circumstellar medium (Cliffe et al. 1995; Steffen & López 1998), and the interaction of the shell with the interstellar medium (Soker & Zucker 1997). See Mellema (1996) for a review of LIS and their models. In addition, other ingredients—such as stellar magnetic fields, rotation, precession, a binary central star, and dynamical (Kelvin-Helmholtz and Rayleigh-Taylor) and/or radiation in situ instabilities—can be considered within these families of models in order to try to match the observations.

2. A LITERATURE SAMPLE OF PNE WITH LIS

We searched in the literature for PNe which present LIS, finding about 50 objects. From this sample, $\sim 50\%$ have jets or jet-like structures and $\sim 35\%$ present other kinds of symmetric LIS (radially symmetrical or point-symmetric pairs). The remaining $\sim 15\%$ are PNe that show LIS more or less oriented in the radial direction, probably being the effect of the ionization front when interacting with density or ionization fluctuations occurring in the circumstellar gas (see, for instance, Soker 1998). Figures 1 and 2 show examples of these classes of LIS in PNe.

In Figure 1, the [N II] image of IC 4593 shows clearly the presence of a very collimated structure of low-ionization. Also in Figure 1, the [N II] image of NGC 6337 shows a nice example of the complexity of the low-ionization structures in PNe. Our spatio-kinematical modeling for this PN reveals that the bright ring is the projection in the plane of the sky of the equatorial density enhancement of a bipolar PN seen almost pole-on, and that the tails and filaments of low-ionization attached to the ring (e.g., the one labeled as C in Fig. 1) have no peculiar velocities compared to that of the ring. These LIS are classified here as non-symmetrical LIS. NGC 3918, in Figure 2, shows two roughly elliptical shells, both elongated in the direction of a highly-collimated LIS, the latter clearly identified in the [N II] light.

Owing to the variety of structures observed, a more precise definition of their properties is necessary. Hereafter we refer to as "jets" the highly-collimated LIS which *i)* are not isolated knots but are extended in the radial direction from the central star, *ii)* appear in opposite symmetrical pairs, and *iii)* move with velocities substantially larger than those of the main shell, whose typical velocities are of $20 - 40$ km s^{-1}. On the other hand, features with the morphological appearance of jets, but which move with velocities similar to those of the main shell, or without available kinematical data, are called jet-like structures (see Figs. 1 and 2). It is clear that projection effects, which are often poorly known, play a fundamental role in distinguishing genuine jets and jet-like LIS. Detailed spatio-kinematic modeling of both the main nebulae and the LIS is therefore mandatory.

3. OUR SAMPLE: NEW DATA ON LIS

We obtained high-quality narrow-band images and long-slit spectra for a sample of PNe: IC 4593 (Corradi et al. 1997); NGC 3918, K 1–2 and Wray 17–1 (Corradi et al. 1999); NGC 6337, He 2–186 and K 4–47 (Corradi et al. 2000); IC 2553 and NGC 5882 (Corradi et al., in preparation). Our goal is to determine the 3D geometrical and kinematic parameters of the nebulae and LIS which can, in turn, constrain the LIS formation models.

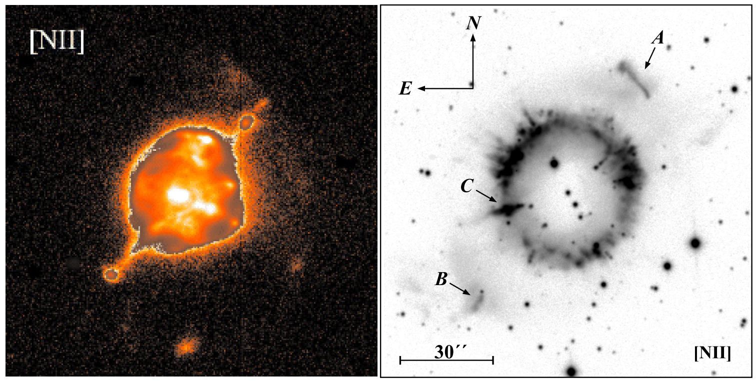

Fig. 1. *Left*: image of IC 4593, from Corradi et al. (1997). The field of view is 45” × 45”, with North at the top and East to the left. Note the collimated structure which is, in fact, a jet-like LIS, since the spatio-kinematical model for the shell and also for the LIS unveils the low velocity of these features. *Right*: Image of NGC 6337, from Corradi et al. (2000). Note the structures attached to the bright ring of emission which are in the radial direction, but that do not form pairs, like C. They are non-symmetrical LIS. Those labeled A and B are embedded in the lobes, one in a direction almost perpendicular to the other.

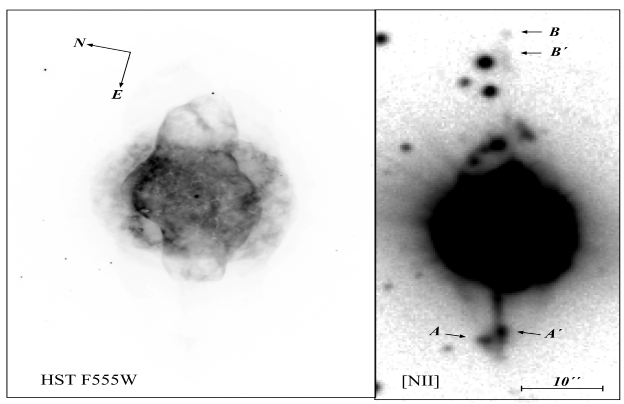

Fig. 2. Images of NGC 3918, from Corradi et al. (1999). *Left*: *HST* image, from which one can identify the inner and the outer shells. *Right*: Ground-based [N II] image. The highly collimated lane of low-ionization emission has high velocity compared to the main shell and, therefore, is an example of jet. Labels AA’ and BB’ indicate the knots at the tip of this two-sided jet.

4. JETS AND JET-LIKE LIS

Most of PNe with LIS do not have published orientational, geometrical and kinematical parameters, which makes a deeper analysis impossible. Others, such as IC 4593 (Corradi et al. 1997), NGC 7009 (Balick et al. 1998), K 1–2 (Corradi et al. 1999), He 2–429 (Guerrero, Vázquez, & López 1999), do have kinematic measurements, but their jet-like LIS show very low radial velocities. After deprojection for inclination (adopting the inclination angle of Reay & Atherton 1985), the LIS in NCG 7009, for instance, would be a real jet, but there are arguments against the jet nature of the structure in IC 4593 (Fig. 1, left). There are other PNe which do contain *bona fide* jets, such as Hb 4 (Hajian et al. 1997), NGC 3918 (Corradi et al. 1999; Fig. 2), K 4–47 and He 2–186 (Corradi et al. 2000).

What kind of features are expected from current jet formation models? If jets are formed by interacting stellar winds (ISW) in the same process in which the main nebulae are formed, then they should have ages similar to that of the main shell and lie along its symmetry axis (or around it, if they are precessing). The case

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of NGC 3918 is very interesting, since it does have a two-sided polar jet coeval with the highly axisymmetrical inner shell (Corradi et al. 1999). However, jets in other PNe such as NGC 6881 appear older than the main shell (Guerrero & Manchado 1998).

Our observations of NGC 3918, He 2–186, and K 4–47 reveal that the collimated gas along the jets is generally increasing in velocity. Could this be an intrinsic characteristic of the collimation process itself? An increase in the expansion velocity is the expected behavior of the jets formed in the models of García-Segura et al. (1999), in which the magnetic field of the central star is responsible for the jet collimation. Note that the collimation processes in the case of K 1–2 (with a close binary system in the center) and NGC 3918, for instance, could not be the same.

5. CONCLUSIONS

We have briefly discussed some of the puzzling characteristics of LIS, particularly jets and jet-like low-ionization structures, in PNe. The need for a good determination of the basic parameters for the main nebular components, and also for the LIS, as well as detailed constraints on the LIS formation models is emphasized. The predictions of the current models, when compared to the observations, are far from satisfactory, and detailed modeling of LIS is clearly a matter that requires urgent attention. To date, the models for jet formation which best agree with observations are those that consider a stellar magnetic field, even though there is no real evidence for the presence of magnetic fields in post-AGB stars or PNe. What kind of direct or even indirect evidence for these fields would one expect?

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