Characterizing Low-Ionization Structures in PNe

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Abstract. Fifty five planetary nebulae containing micro-structures of low-ionization (LIS) are analyzed in this review in terms of LIS morphology, kinematics, and physical and excitation properties. We attempt to address the issue of their origin through the comparison of LIS properties with the main shells of the nebulae, as well as the contrast with the theoretical model predictions. We finally conclude that, while LIS morphology and kinematics can be reasonably accounted for by the available theoretical models, they cannot explain the LIS physical/excitation properties, unless we agree that evolved PNe are expected to show neither shock-excited LIS nor significant density contrasts relatively to their environments. Some evidence for the latter ideas is actually presented in this paper.

1. Introduction

Low-ionization ‘microstructures’ of planetary nebulae (PNe) are those structures that are much more prominent in [N ii], [S ii], and [O ii] than in the [O iii] or Hα emission lines. The low-ionization structures (LIS, Gonçalves et al. 2001) appear with different morphological and kinematical properties in the form of pairs of knots, filaments, jets, or isolated features moving with supersonic velocities through the large-scale components in which they are located, or instead as structures with the above morphologies but with low velocities that do not differ substantially from that of the main nebula1. For the sake of conciseness, the complete table listing all known LIS will not be reproduced here; however, readers are referred to the web page at www.iac.es/galeria/denise/PNe_LIS.html where the morphology and kinematics of LIS, as compared to those of the main PN bodies, are shown. This table, adapted from Gonçalves et al. (2001), also includes those ‘new’ objects whose LIS were identified after 2001.

It is important to keep in mind the number of PNe that are known to possess LIS. These amount to 55 objects. If we consider the number of Galactic PNe imaged with at least one filter of higher and another of lower ionization (Balick 1987; Schwarz et al. 1992; Manchado et al. 1996), we end up with 527 PNe. Therefore, about 10% of the Galactic PNe are actually confirmed to have LIS.

1The fast, low-ionization emission regions, FLIERs (Balick et al. 1993) and bipolar, rotating, episodic jets, BRETs (López et al. 1995) are particular types of LIS, i.e., high-velocity knots and jets.
2. Types of LIS from their Morphology and Kinematics

Many authors, as can be noted from the above-cited table, have been working on the characterization of LIS. So the reader is referred to the list in the table in order to obtain information on the morphology/kinematics for each of the objects listed. On the other hand, Gonçalves et al. (2001) offers a detailed study concerning the morphological and kinematic classification of LIS as compared to theoretical model predictions, where the authors gather together 50 PNe containing LIS, with all their different types (see Figure 1). Also check Tables 2 to 5 of Gonçalves et al. (2001) for the kinematical ages, positions and orientations of LIS with respect to the rim and the major axes of the PN main bodies). The most relevant conclusions, reached from the morphology and kinematics of LIS, are shown below.

Figure 1. Examples of the different types of LIS. From top to bottom, we show two PNe with low-ionization pairs of jets, jetlike pairs, pairs of knots, and finally the isolated structures.
2.1. Pairs of Jets
Most of the properties of jets in NGC 7009, NGC 6891, and NGC 3918 can be explained by HD and MHD interacting stellar wind (ISW) models. The observed linear $v_{\text{exp}} \times d$ (distance from the center) would favor the MHD (García-Segura et al. 1999) and the stagnation jet (Steffen et al. 2001) models. K 4-47, M 1-16 and Fg 1 would better be explained by accretion disk jet models (Blackman et al. 2001); while Hb 4, NGC 6210, and NGC 6543, showing jets which are kinematically younger than the main PNe shells, do not fit within the predictions of any model. Some jets have large (say $90^\circ$) jet–nebula angles (Hb 4, NGC 6210, and NGC 6884). It is still not clear if the magnetic/rotation axis and polar axis misalignments (García-Segura & López 2000; Blackman et al. 2001) can account for large tilt angles like these.

2.2. Jetlike Pairs
IC 4593, He 2-429, NGC 6881, K 1-2, Wray 17-1, and probably NGC 6751 show features that are very much like jets, but that are moving with velocities which do not differ substantially from those of the PN main bodies (see Corradi et al. 1997, 1999; Guerrero et al. 1999). Models only predict high-velocity jets instead of jetlike features, with the exception of the transient low-velocity collimated micro-structures of the Soker (1992), Różycka & Franco (1996), and Steffen et al. (2001) models.

2.3. Pairs of Knots
Symmetrical high-velocity pairs of knots can, in principle, be accounted for by HD or MHD interacting stellar winds, accretion disk winds, or stagnation zone models, since models for the jet formation can also easily explain the origin of pairs of knots. The non-detection of the outward-facing bow shocks that should be associated with these features might be caused by instabilities (HD/radiative; Soker & Reveg 1998). On the other hand, pairs of low-velocity knots are less studied theoretically. We suggest that fossil AGB knots, implying a very peculiar AGB mass-loss geometry, could be responsible for at least some of the low-velocity pairs of knots.

2.4. Isolated LIS
Isolated LIS may be formed by in situ instabilities and/or by fossil AGB mass-loss inhomogeneities. However, from their positions with respect to the rim (the shell formed by the interaction between the AGB and the post-AGB winds), they are not related to dynamical instabilities because of the action of the fast post-AGB wind (see Table 5 of Gonçalves et al. 2001). The rocket effect (Mellema et al. 1998) could, in some cases, explain the peculiar velocities of the high-velocity isolated LIS.

3. The Physical Parameters and the Excitation Properties of LIS
From the above, it seems clear that at least part of the LIS characteristics can be reasonably explained by the different models intended to account for their formation, at least in terms of morphology and kinematics. Now, which are
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Figure 2. The HST archive [N II] image of NGC 7009 with its many structures, and the $T_e$ and $N_e$ associated with these structures.

the observables for further comparison with models? How we can go further in distinguishing between the various physical processes for the origin of LIS?

Densities or density contrasts of LIS are reported in the literature for many PNe individually. Balick et al. (1994) and Hajian et al. (1997) dealt with physical properties in a group of PNe with high-velocity pairs of knots (FLIERs). We are now trying to answer issues such as: i) whether the density contrast plays a role on the low-velocity LIS; ii) whether the low-density pairs could be features slowed down by the medium (since they are more easily stopped); and iii) whether the high-density knots might originate in mass-loss episodes prior to PN formation. We are dealing with these questions by analyzing not only FlierRs but also the other types of LIS, i.e., the low-velocity ones.
What about the excitation mechanisms of the low-ionization structures? Should we observe shocked–excited emission from the high-velocity LIS (Dwarkadas & Balick 1998; Soker & Reveg 1998)?

Let us analyze the case of NGC 7009 (which shows one of the best known jets in PNe) and then compare its characteristics with those of other PNe with low- and high-velocity pair of knots, as well as jets.

### 3.1. \(T_e, N_e\) and the Excitation of NGC 7009

The physical, chemical, and excitation properties of NGC 7009, including its pair of jets (J1, J2), inner (K2, K3) and outer (K1, K4) pairs of knots, and the rim (R1, R2), were recently studied by Gonçalves et al. (2003); see Figure 2. This is one of the PNe in our sample observed with the 2.5 m INT (ORM, La Palma, Spain), in August 2001. Our spectra were taken at P.A. = 79° (slit width = 1″.5, slit length = 4″) and cover the optical range from 3700 Å to 6750 Å, with 3.3 Å pix\(^{-1}\) and 0″.70 pix\(^{-1}\) resolutions (see also Gonçalves et al., this volume).

As is clear from Fig. 2, the \(T_e\) throughout the nebula is remarkably constant, \(T_e[\text{O III}] \approx 10\,200\) K; the bright inner rim and inner pair of knots have similar densities of \(N_e[\text{S II}] \approx 6000\) cm\(^{-3}\), whereas a much lower density of \(\sim 1500\) cm\(^{-3}\) is derived for the outer knots, as well as for the jets. This implies that the outer pair of knots, being as dense as the jets, cannot originate from the matter swept up by jets, as expected from some model predictions (see discussion below).

We use two relevant diagnostic diagrams (Phillips & Cuesta 1999) to investigate the excitation of the selected features in NGC 7009 (Figure 3). These diagrams separate the zones of radiatively excited emission lines (the PN zone) from the zone mainly excited by shocks. It is clear that all eight structures in NGC 7009 are mainly radiatively excited by the central star of the PN.

### 3.2. \(T_e, N_e\) and the Excitation of Other PNe with LIS

In Table 1 we collect the \(T_e\) and \(N_e\) of some PNe with jets/knots. In the second and third columns, these properties for the main shell (rim) are shown, followed by those for the jets/knots in the same PNe. Note, from the table, that most jets/knots are between 2 and 10 times less dense than the nebular main bodies.
or their surroundings (the exceptions being K 4-47 and NGC 6210). What does this mean? Have the density contrasts been erased by the knots’ expansion because of the ionization process, as suggested by Soker & Reveg (1998)?

In the diagnostic diagrams, presented in the previous section, we actually put together many PNe. Please take into account that the microstructures in Figure 3 are real jets, jetlike systems, and both high- and low-velocity pairs of knots. The first important result we can extract from these plots is that low-velocity LIS (in He 2-429 and He 1-1) cannot be separated from the high-velocity ones (all the others), most of them being distributed in the PN zone (an emission characteristic of photoionization instead of shock excitation) or above it. Second, only a few LIS (those of Kj Pn 8, K 4-47, and M 2-48) are mainly excited by shocks. These three PNe appear to be the youngest in the sample. Are the jets/knots in the other, more evolved, PNe ‘relaxed’ in the sense that the once shock excited LIS were reached by the central star ionization front, which came to be the most relevant excitation process?

4. Discussion and Conclusions

In summary, what do we really know about LIS in PNe? From the observations:

1. LIS appear as pairs of jets, knots, filaments, and jetlike features, or as isolated systems;
2. Sometimes LIS expand with the rim, shells or haloes in which they are embedded, but sometimes they are much faster than the main PNe components;
3. They are spread indistinctly within all the morphological classes of PNe;
4. In general, they do not have an important density contrast with respect to the main bodies; and
5. Most LIS systems studied up to now are mainly photoionized.

Concerning the comparison of LIS properties with the theoretical predictions, some of their characteristics appear hard to explain (see Balick & Dwarkadas 1998; Gonçalves et al. 2001, 2003; Balick & Frank 2002). However, the origin of part of these systems (from their morphology and kinematics) can be reasonably understood via ISW models, in single stars or binaries, with or without magnetic fields, precession, and wobbling.

The fact that the expected shock excitation of jets and other high-velocity LIS is not usually observed could mean that jets/knots are relaxed systems in the sense that shock excitation and high density contrasts are no longer present because LIS were already reached by the energetic photons of the post-AGB central star, and/or affected by local instabilities (Dopita 1997; Miranda et al. 2000; Soker & Reveg 1998). Finally, it is remarkable that both shock excited LIS and LIS with high density contrasts are found in young PNe. This may imply that jetlike systems and low-velocity pairs of knots are the remnant of real jets and high-velocity pairs of knots, which suffered the effects of drastic slowing down and photoionization, being therefore, found in more evolved PNe.

References

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Figure 3. Diagnostic diagrams showing the position of the emission-line ratio characteristics of shock-excited objects (SNR, shock regime) and the photoionized (PNe, HII) ones. References for the data: Fg 1, Vázquez et al. (1998); PC 19, He 2-249, and He 1-1, Benítez et al. (2002); Kj Pn 8, López et al. (1995); NGC 7009, Gonçalves et al. (2003); and NGC 6891 and K 4-47, this work.
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