A New Diagnostic for Fast Outflows in Planetary Nebulae

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Summary. Fast collimated outflows have proven ubiquitous in planetary nebulae (PNe) and their dynamical action can be very important in the PNe formation and shaping. Using a database of *HST* WFPC2 images of 64 PNe, we explore in this work a new diagnostic for fast collimated outflows in PNe based on the effects that their shocks produce in the relative [O III] and Hα emissions. We confirm that the [O III]/Hα ratio is enhanced in thin skins associated to bow-shocks of fast collimated outflows, but we also find that low velocity shocks associated to expanding shells of multiple shell PNe produce similar effects. These results indicate that the occurence of a thin skin of bright [O III]/Hα in a PN is not sufficient to confirm the presence of a fast collimated outflow, but it can always be connected with the effects of a shock.

Key words: ISM: collimated outflows — planetary nebulae: general

1 Introduction

Jets and collimated outflows may have important dynamical effects in planetary nebulae (PNe), contributing decisively to the nebular shaping. Fast collimated outflows in PNe can drive shocks in the surrounding medium that can be detected through:

- morphological effects: bow-shock structures,
- excitation effects: regions of enhanced emission in low-ionization lines,
- dynamical effects: broadened emission lines,
- hot gas: X-ray emission for shock velocities greater than 300 km s^{-1}.

Narrow-band imaging in low-ionization emission lines (e.g., [N II] or [O I]) are typically used to detect fast collimated outflows in PNe, although the presence of low-ionization features that are not moving at high speed is sometimes confused with fast collimated outflows (Balick et al., 1993). High-dispersion spectroscopy can be used to determine the real nature of low-ionization features, but these observations are insensitive to fast collimated outflows moving along the plane of the sky (Corradi et al., 1997).

In addition to the effects listed above, a fast outflow propagating into a low density medium drives a forward shock that produces an increase of T_e. The high temperature and low density of the medium enhance the emission in the [O III] λ5007 Å line, which is very sensitive to T_e, while the emissivity of the Hα line, which is more sensitive to N_e, is reduced. Consequently, a region where the [O III]/Hα ratio is significantly enhanced develops in front of the collimated outflow. This effect is observed in wind-blown bubbles around WR stars. In S 308, for instance, the shell expanding at 65 km s^{-1} generates a forward shock that produces a notable offset between the [O III] and Hα emissions (Gruendl et al., 2000).

Recently, Balick (2004) found a thin skin of enhanced [O III]/Hα enveloping NGC 6543 in *HST* WFPC2 images of this nebula. The origin of this skin of enhanced [O III]/Hα, while uncertain, was excluded to be an observational artifact. The association of the structure observed in NGC 6543 with its collimated outflows is tantalizing. Here we explore the use of [O III]/Hα ratio maps to detect fast collimated outflows in PNe.

2 PN Classification Based on the [O III]/Hα Ratio

Inspired by the results obtained for NGC 6543, we have used the WFPC2 [O III] and Hα images of all PNe available in the *HST* archive to investigate the occurrence of skins of bright [O III]/Hα in PNe and its relationship with fast collimated outflows. The sample of PNe with useful *HST* WFPC2 [O III] and Hα images includes 64 objects. The [O III] and Hα images were processed using standard pipeline procedures and the images were registered and shifted to obtain the [O III] to Hα ratio image. The [O III]/Hα ratio maps were subsequently examined to investigate the relative positions of the [O III] and Hα emissions and to search for regions of enhanced values of the [O III]/Hα ratio.

The spatial differences between the [O III] and Hα emissions are clearly highlighted by the [O III]/Hα ratio images (see Figure 1 for a few examples). In a number of cases, the ratio maps show regions of bright [O III] emission external to the nebular shell or at the tip of jet-like features. In some other cases, a region of bright Hα emission relative to [O III] surrounds the nebula. A close inspection of the [O III]/Hα ratio images of these PNe has allowed us to classify them into four different types:

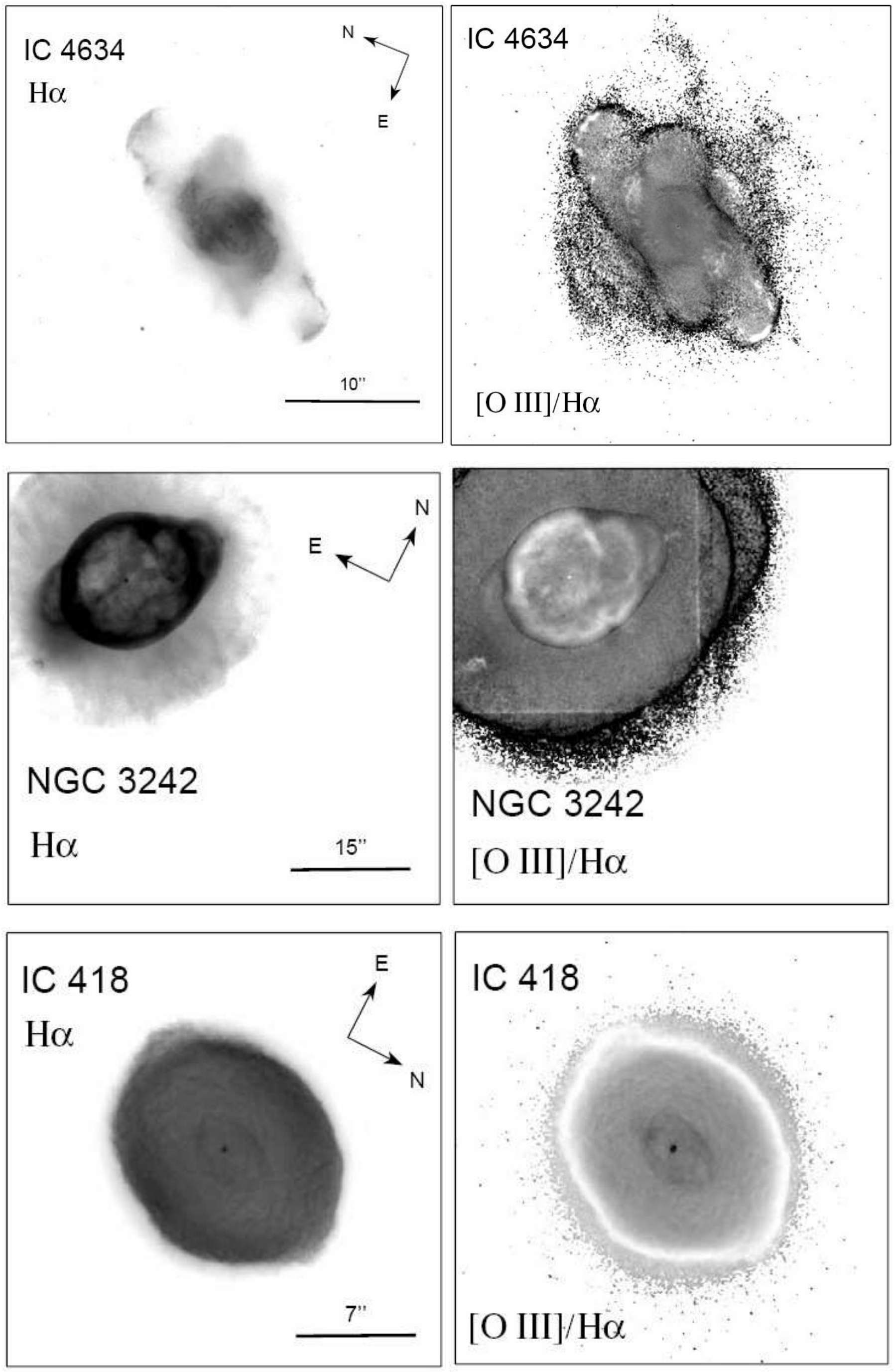

Fig. 1. Hα and [O III]/Hα ratio images of the type A PN IC 4634 *(top)*, type B PN NGC 3242 *(center)*, and type C PN IC 418 *(bottom)*. In the [O III]/Hα ratio images, regions of relatively bright Hα emission appear bright (white), whereas regions of strong [O III] emission relative to Hα are shown dark (black).

- **Type A**
  PNe surrounded by skins of enhanced [O III]/Hα that can be associated to bow-shock features produced by fast collimated outflows. Type A PNe are IC 4634 (Fig. 1-top), NGC 6210, NGC 6543, NGC 6572, and NGC 7009.
- **Type B**
  PNe surrounded by skins of enhanced [O III]/Hα emission associated to nebular shells. In some double-shell PNe, both shells exhibit a skin of enhanced [O III]/Hα. The list of type B PNe includes NGC 3242 (Fig. 1-center), NGC 6153, NGC 6210, NGC 6818, NGC 6826, NGC 7009, and NGC 7662. Although some type B PNe display FLIERs, the skin of enhanced [O III]/Hα does not seem to be related to these features.
  Note that NGC 6210 and NGC 7009 also show regions of bright [O III]/Hα ratios that can be associated to bow-shock features produced by fast collimated outflows. For these two PNe, we will use the **type AB**.
- **Type C**
  PNe where the [O III]/Hα ratio decreases at the outer edge of the nebula, i.e., these PNe show the opposite behavior to type A and B PNe. Among these PNe are: BD+30°3639, IC 418 (Fig. 1-bottom), IC 5117, Hen 2-447, Hen 3-1357, M 1-20, M 1-61, M 2-14, NGC 3132, NGC 6572, NGC 6720, NGC 6790, NGC 6881, and NGC 6886.
  NGC 6572 also shows a region of bright [O III]/Hα associated to a bow-shock feature. For this PN, we will use the **type AC**.
- **Type D**
  The remaining $\sim$30 PNe (i.e., $\sim$50% of the PNe in our sample) have [O III]/Hα ratio maps that do not show any of the effects described above, either because the ratio maps are flat, have low SNR, or show too complex structures.

3 Discussion and Summary

PNe of types A and B are well-resolved objects with multiple-shell morphology. The temperature and luminosity of their central stars and their nebular densities indicate that these PNe are not yet in a late evolutionary status. The occurrence of collimated outflows is higher among PNe of type A, while a significant fraction of PNe of type B exhibits FLIERs, suggestive of fast collimated outflows, although with expansion velocities comparable to these of the nebular shells.

PNe of type C tend to be small, but NGC 2346, NGC 3132, and NGC 6720 have the largest angular radii and linear sizes in the sample. PNe of type C are either young, with low (<50,000 K) $T_{\rm eff}$ central stars (e.g., BD+30°3639 and I 418), or evolved, with hot, low luminosity central stars (e.g., NGC 3132 and NGC 6720). In both cases, the ionizing flux of these stars is not sufficient to ionize all O in the nebula up to O^{++}.

Type D PNe is a heterogeneous group severely affected by several observational biases. Most type D PNe are small, with angular radii $\leq 4''$, and have images of low SNR. The small size of these objects is clearly introducing an observational bias in the sample, as we cannot resolve details in these objects. On the other hand, some objects in this group are large and well resolved, but they have very complex morphologies (e.g., Hb 5, NGC 2392, and NGC 2440) which are probably hiding some of the effects exhibited by PNe of type A, B, or C.

Photoionization models can easily reproduce the observed [O III]/Hα ratio maps of type C PNe in terms of a nebular ionization structure in which the O^{++}/H^{+} ratio decreases in the outermost region. However, the observed [O III]/Hα ratio maps of type A and B PNe cannot be reproduced by these models, unless an *ad hoc* additional heating mechanism working on small spatial scales produces a sharp raise in T_{e}. The forward shock of a fast outflow propagating into a tenuous medium (type A PNe), or a dense shell expanding into a low density outer shell (type B PNe), can cause this extra heating.

To sum up, we have used *HST* WFPC2 [O III] and Hα images of a sample of 64 PNe to study the spatial variations of the [O III] and Hα emissions associated to the shocks driven by fast collimated outflows. We have confirmed that the enhancement of the [O III]/Hα ratio in thin skins is, indeed, preferentially associated to PNe with fast collimated outflows. Observations of the greatest depth and spatial resolution are needed in order to reveal these effects. Furthermore, we have found that low velocity shocks associated to expanding shells of multiple shell PNe seem to be able to produce similar effects. These results indicate that the discovery of thin skins of bright [O III]/Hα ratios is not sufficient to prove the presence of fast collimated outflows, but they illustrate the complexity of PNe and its suitability to studying the physics of ionized plasmas.

Acknowledgments

This work is funded by grants PNAYA2005-01495 (Ministerio de Educación y Ciencia, MEC), FGM-1747 (Junta de Andalucía), and 2006-50-I135 (Consejo Superior de Investigaciones Científicas, CSIC).

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