The Ionization Structure of a Sample of Wind-Driven Nebulae

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Introduction

- The study of the environments of stars provides important clues to their evolution. The history of a changing stellar output of winds and ejecta can be discovered in the environments of massive and intermediate mass stars. Wolf-Rayet Ring Nebulae (WRN), surrounding the evolved descendant of **massive OB stars**, and multiple shell planetary nebulae (MSPNe), constitute ideal laboratories to study the history of the stellar mass loss written in these wind-driven nebulae. These nebulae are surrounded by faint structures such as shells, haloes and other irregular outer structures. These outer haloes are of great interest as they are presumably the remains of the original stages of mass loss from the progenitor stars.

- The **aim** of this work is the study of the energetics and dynamical evolution of the final stages of intermediate and massive stars through the observation and physical modeling of their nebulae. Our project includes the study of ionization structure of these nebulae, and the detection of a possible shock-heated gas component. The approach followed on this subject is based in the determination of the 2D ionization structure of the haloes and outer shells of a selected group of nebulae.

Evolutionary Facts :

- Long-slit observations of the haloes of some MSPNe (e.g. NGC 6543, NGC 6826, and NGC 7662) have shown that the haloes are hotter than their respective cores (Manchado & Pottasch 1989, Meaburn et al. 1991, Middlemass et al. 1989, Middlemass et al. 1991). Middlemass et al. have shown that photo-electric heating is not able to reproduce the high temperatures observed in the halo of NGC 6543, and an extra heating source is required. A candidate for the extra energy source is the fast wind passing the cold filamentary knots observed in the haloes of these Planetary Nebulae.

- A similar scenario is expected to operate in the WRN, which should be consistent with the general evolution of massive stars through a high mass loss towards the WR phase. This evolution produces a sequence of fast wind plus slow ejecta plus WR fast wind that can explain many of the observed morphologies.

Observations

This work is part of an observational program aimed to study the ionization structure and the fine-scale structures in the haloes of MSPNe and WRNe.

As a first approach to this subject, we have obtained narrow band images of a selected group of MSPNe and WRNe, using narrow-band filters including low-ionization (e.g. [S II]) and high ionization species (e.g. [O III]).

The comparison of the emission from different states of ionization or different emissivity conditions provides direct evidence for fine-scale structure within the haloes of the nebulae.

Narrow-band images were obtained with the 2.5 m INT of the ORM (La Palma, Spain) with the Wide Field Camera (WFC), and at the 2.2 m Telescope at Calar Alto (Almeria, Spain) using the Bonn University Simultaneous Camera (BUSCA) during three runs (2002 from July to December). In total we have obtained images of 17 nebulae (including MSPNe and WRNe). Table 1 summarizes these observations.

The Sample

OBJECT	RA	Dec	Type	Instrument	Filters
NGC6543	17:58:33.40	+66:37:58.9	PN-halo	INT-WFC	Hα, [OII], [OIII], [SII],B, r, g
NGC6888	20:12:26.90	+38:21:17.6	PN-halo	INT-WFC	Hα, [OII], [OIII], B, r, g
WR102	17:45:47.00	-26:10:29.0	WR-ring	INT-WFC	Hα, [OII], [OIII], [SII],B, r, g
NGC7662	23:25:53.99	+42:32:06.0	PN-halo	INT-WFC	Hα, [OIII], r, g,
NGC7662	23:25:54.00	+42:32:06.0	PN-halo	CAHA 2.2-BUSCA	[NeIII], [OIII], Hα, Hβ, [SIII],V,b,y,I
M 1-67	19:11:30.89	+16:51:38.1	WR-ring	CAHA 2.2-BUSCA	[NeIII], [OIII], Hα, Hβ, [SIII],V,b,y,I
M 1-67	19:11:30.89	+16:51:38.1	WR-ring	INT-WFC	Hα, [OII], [OIII], [SII], B,g, r
NGC6826	19:44:48.00	+50:31:30.0	PN-halo	CAHA 2.2-BUSCA	[NeIII], [OIII], Hα, [SIII],V,b,y,I
NGC6720	18:53:35.00	+33:01:43.0	PN-halo	CAHA 2.2-BUSCA	[NeIII], [OIII], Hα, [SIII],V,b,y,I
NGC6894	20:16:24.00	+30:33:54.0	PN-halo	CAHA 2.2-BUSCA	[NeIII], [OIII], Hα, [SIII],V,b,y,I
NGC6210	16:44:29.00	+23:48:00.0	PN-halo	CAHA 2.2-BUSCA	[NeIII], [OIII], Hα, Hβ, [SIII],V,b,y,I
NGC6804	19:11:31.00	+09:13:31.0	PN-halo	CAHA 2.2-BUSCA	[NeIII], [OIII], Hα, Hβ, [SIII],V,b,y,I
NGC7009	21:04:11.00	-11:21:50.0	PN-halo	CAHA 2.2-BUSCA	[NeIII], [OIII], Hα, [SIII],V,b,y,I
NGC6891	20:15:09.00	+12.42.17.0	PN-halo	CAHA 2.2-BUSCA	[NeIII], [OIII], Hα, [SIII],V,b,y,I
NGC246	00:47:03.34	-11:52:19.0	PN-halo	CAHA 2.2-BUSCA	[NeIII], [OIII], Hα, [SIII],V,b,y,I
NGC2359	07:18:29.09	-13:13:01.5	WR-ring	INT-WFC	Hα, [OII],[OIII], [SII],r,g
S308	06:50:50.9	-23:49:14.0	WR-ring	INT-WFC	Hα, [OII], [OIII], [SII], r, g

Data reduction

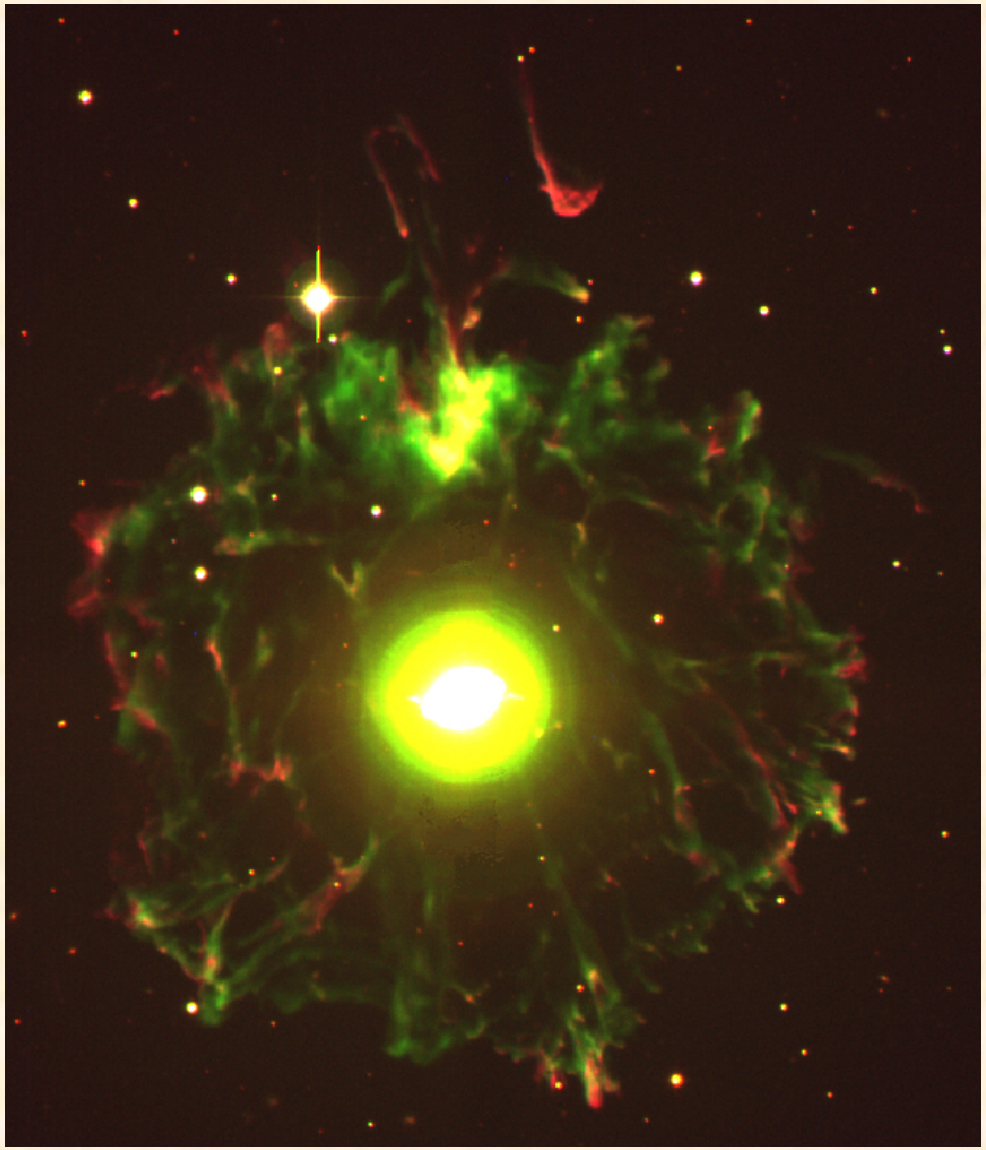
We followed *standard image reduction* techniques for bias-substracting, flat-fielding, and removing cosmic rays using the IRAF packages. Bad columns were removed using neighboring replacement techniques.

The study of the haloes of these nebulae requires a careful determination of the *scattered light* from the bright cores (see Corradi et al. 2003). We determined the underlying scattered continuum light level at the location of the fine-scale structure of the haloes, which was *subtracted* accordingly in order to produce the corresponding line-ratio images.

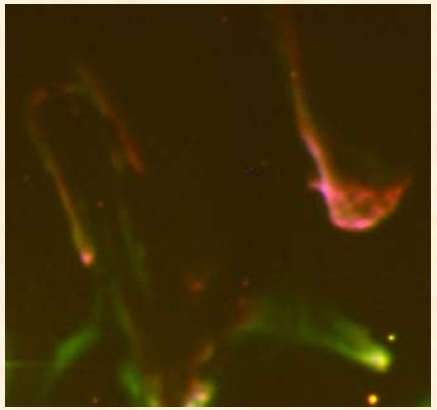
Absolute flux calibration was accomplished using several spectro-photometric standard stars which were observed throughout every night. Sequences of images with different exposure times were obtained in order to sample the large dynamic range of these nebulae. The flux per pixel of the central core is ~ 3-4 orders of magnitude higher than the faintest parts of the halo. Saturated pixels (in the core of the nebulae) in long exposures are masked out in the pictures shown here of NGC 6543.

Ionization Structure Examples :
a) the Halo of NGC 6543

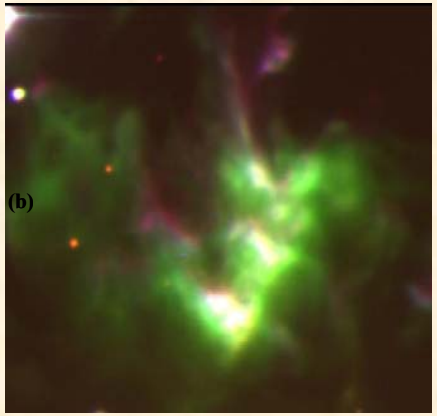
(a)



(b)



(c)





(d)

Figures 1: (a) The composite image of NGC 6543 made with Hα + [N II] = (RED) , [O II] = (BLUE) and [O III] = (GREEN) emission line images displayed with linear intensity.

This color image is made of three RGB 8-bit images.

These images show the fine-scale structures of the halo of the nebula.

Figures 1 (b) , and 1 (c) show outstanding structures seen in the halo of NGC 6543 with the same color combination as in Fig. 1a.

Figure 1 (d) represents a close-up of Figure 1 (a) showing the "ionization color" of the well known concentric rings structure observed in NGC 6543 (e.g. Balick, Wilson & Hajian 2001).

- **Preliminary findings: the halo of NGC 6543**

- To ***illustrate the scope of this project*** we have chosen the images of the ionization structure of the halo of the well known PN NGC 6543. Since this object has been extensively studied in the recent literature, it provides a useful laboratory to test our approach and to illustrate some of the possibilities of the study of the ionization structure, [see Figures 1, 2 and 3]. Despite the fact that the central parts of the nebula have been studied in detail, the figures show that there remain still some aspects of the spatial structure of the ionization which deserve further insight and that can provide useful constraint to photoionization modeling.

- The irregular halo of NGC 6543 contains numerous filaments and knots, with a complex ionization structure. Some of the radial filaments are dominated by the [OIII] emission, while some other features show low-ionization (i.e. are dominated by Hα+[NII] and [OII] emission). Figures 2 and 3 illustrate the complex ionization structure of this object. Figure 1 shows the variation of the ionization structure of the bow shock-like feature seen west of the central core, with the [OII] lying nearest and with the [OIII] emission on the far side of the central source. This ionization structure is not consistent with either an ionization front or a recombination region of a shock. These line ratios maps are not consistent with the mass-loaded outflows leaking through the inner core and colliding with clumps pre-existing in the haloes (see e.g. Middlemass et al. 1991; Arthur, Dyson & Hartquist 1994).

Halo Ionization Structure Faint Features

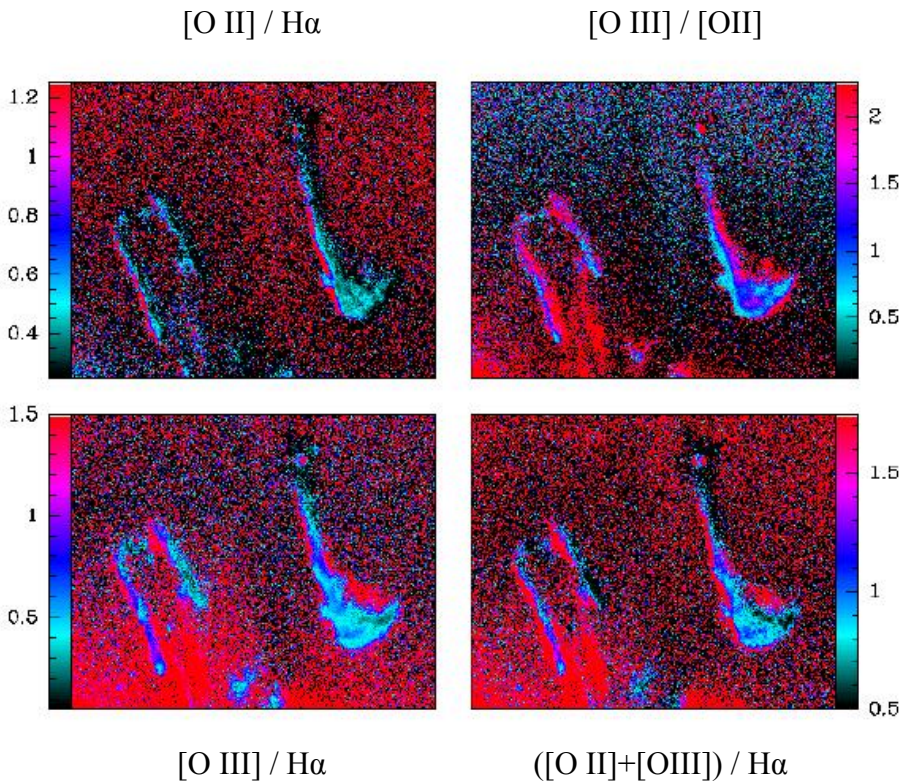


Figure 2: **Ionization structure ratio maps** (relative) using the flux calibrated images. The emission line ratios [OIII] 5007/(Hα+[NII]), [OII] 3727/(Hα+[NII]), [OIII]/[OII] and ([OIII]5007+[OII]3727)/(Hα+[NII]) are shown for the filamentary and bow shock-like structures (as seen in Figure 1).

NGC 6543

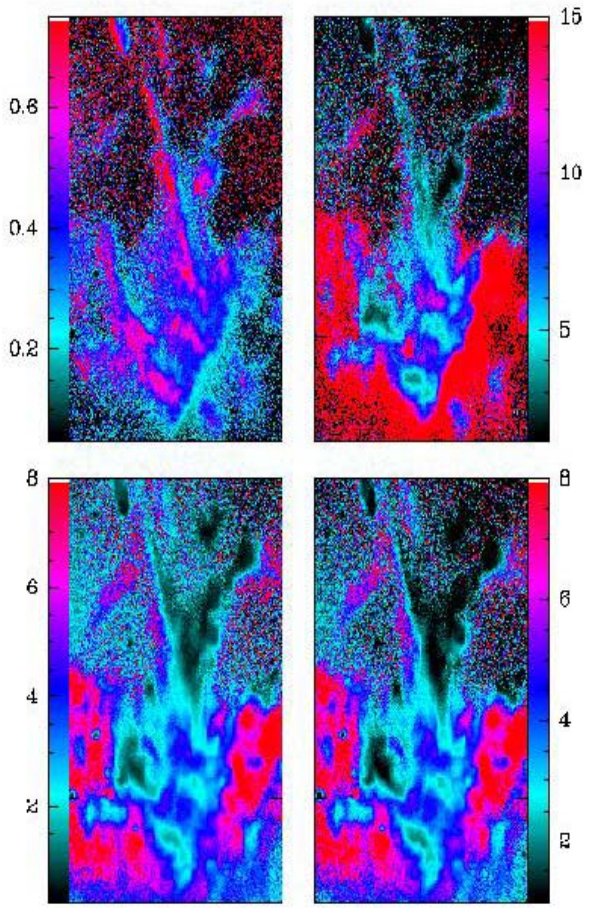


Figure 3: **Ionization structure maps** (relative) of the brightest knot observed in the halo of NGC 6543 obtained using flux calibrated images (as in Figure 2).

WR 102

- The central star is a very massive WR star of type WO.



Work in Progress

a) High (spectral & spatial) resolution spectrophotometry of candidate nebulae selected form our 2D Ionization Structure Maps.

b) Physical Modelling:

i) 1D photoionisation models (& Shock Heating)
ii) Diffuse ionization contribution
iii) Chemodynamics & empirical yields

c) Near Infrared & Optical high resolution imaging + A.O. techniques of the WR circumstelar nebulae and some Luminous Blue Variables.

- **References used for this presentation**

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