NLTE Analysis of Central Stars of Highly Excited Planetary Nebulae

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Introduction

Very hot central stars (CSPN) of highly excited planetary nebulae (PN) display directly the formation of white dwarfs: At the hottest stage of evolution they are close to the end of nuclear burning and gravitational effects become dominant. Only a few of these CSPN have been analyzed so far due to their low brightness and thus, the interpretation of their evolutionary status is hampered by statistical incompleteness.

In the last decade many spectral analyses of very hot ($T_{\rm eff}\gtrsim$100 kK) post-AGB stars by means of state-of-the-art NLTE model atmospheres have been performed (Rauch et al. 1994; Werner 1991; Werner & Rauch 1994; Werner et al. 1991, 1995) and our picture of post-AGB evolution has been improved. These analyses include the extremely hot He-rich PG 1159 stars (about every other of them has an associated PN).

In recent analyses of the He-rich CSPN of K 1-27 ($T_{\rm eff}=110$ kK, $\log g = 6.5$, Rauch et al. 1994) and LoTr 4 ($T_{\rm eff}=120$ kK, $\log g = 5.5$, Rauch et al. 1996), an evidence was found that these objects are either progenitors of PG 1159 stars or evolve directly into white dwarfs. Although they are in a late stage of their evolution, their PN are apparently small ($d\approx 60$" and 40", respectively). Thus, spectral analyses of CSPN with "smaller" PN will allow a close look onto the WD-formation scenario. These objects had totally been neglected before.

Aims of this Investigation

This work aims at

→ spectroscopy and spectral classification of the CSPN

- spectral analysis of the CSPN by means of NLTE model atmosphere techniques
- discovery of PG 1159 stars: Napiwotzki & Schönberner (1995) analyzed 39 northern CSPN and found seven new PG 1159 stars

→ imaging (H α and [O III] λ 5007 Å) of the PN

- information about spatial distribution of matter
- information about ionization within the PN

→ spectroscopy of the PN — by-product (background) of the CSPN (longslit) spectroscopy

- analysis of the PN with photoionization models (Köppen 1979)

Observations

We selected southern CSPN ($m_V = 16-18.5$) of highly excited PN with diameters $>$ 18-180" (Acker et al. 1992). Images as well as medium resolution ($\approx$ 8 Å) spectra had been taken in two observation campaigns in February and June 1996 at ESO with the 3.6m telescope. The targets are summarized in Tab. 1.

Table 1. List of our targets. Given are the visual magnitudes of the CSPN, the diameter d and the excitation class (EC) of the PN, and the number of exposures (n, later co-added)

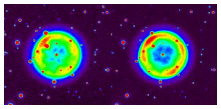
name	m_V	d/"	EC	n	comments
PN G214.9+07.8	16.6	67	7	1	A 20
PN G231.8+04.1	18.0	64	5	2	NGC 2438
PN G249.3−05.4	18.5	54	5	2	A 23
PN G253.5+10.7	16.6	58	7	2	K 1-2, binary
PN G257.5+00.6	18.0	61	5	1	UBRC 1
PN G277.1−03.8	16.5	90	5	1	NGC 2899
PN G283.6+25.3	17.4	180	5	1	K 1-22
PN G293.6+10.9	18.0	82	5	2	BlDz 1
PN G324.1+09.0	17.1	18	7	1	ESO 223-10

Spectral Analysis of the Central Stars

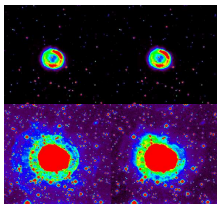
Medium resolution spectra of all targets but PN G324.1+09.0 (Tab. 1) have been taken with EFOSC 1 and the B 150 grism. The exposure times were 3600 sec. We achieved a resolution of about 6 - 8 Å. In Fig. 1 the normalized spectra are shown compared with theoretical spectra. In the data reduction it has been impossible to subtract completely the nebula emission lines [O III] $\lambda\lambda$ 4959, 5007 Å due to strong asymmetries. However, the other nebula emission lines could be sufficiently eliminated. For a preliminary analysis of the spectra we used H-He NLTE models (Werner 1986).

Imaging of the Planetary Nebulae

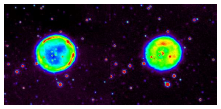
We took H α (left) and [O III] λ 5007 Å (right) images (exposure time 900 sec each) of all PN from Tab. 1 with EFOSC 1 (CCD ESO #26, TEK 512M, 512 x 512 px, 1 px = 0.609" projected at the sky). The images are flatfielded with suitable sky flats. The size of the fields shown here is indicated in arc seconds (in brackets). The diameters of the PN are given for W-E ($d_{\rm WE}$) and N-S ($d_{\rm NS}$) direction. For all images, North is up and East is right. The intensity is encoded with a rainbow color table: black is the lowest, red the highest intensity. For PN G231.8+04.1, PN G257+006, and PN G277.1−03.8 the same images are displayed with different cut levels in order to show the fainter structures of the PN.



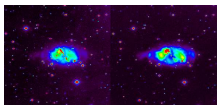
PN G214.9+07.8 (147" x 147")
perfectly circular shape with a diameter of 96", central hole with radial "cartwheel" structures, small shell just outside the main nebula, weak but present polar lobes



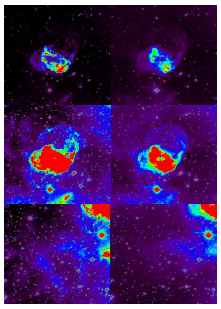
PN G231.8+04.1 (298" x 298")
cuts: upper images 0:15000, lower 0:200
quite circular multiple-shell PN with prominent central hole, polar lobes, distinct faint outer shell, and a large very faint halo; all three shells are fairly regularly shaped (diameter 250")



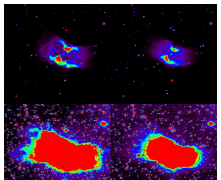
PN G249.3−05.4 (147" x 147")
circular PN with prominent central hole, $d_{\rm WE}$= 69", $d_{\rm NS}$=63"



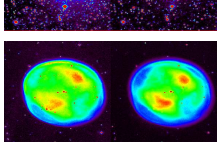
PN G253.5+10.7 (241" x 241")
elliptical PN with a strong central hole and "ansae" quite prominent in [O III]; one notes two thin jet-like features aligned with the central star, 60° off the axis connecting the ansae and the two main [O III] emission blobs, $d_{\rm WE}$= 147", $d_{\rm NS}$=83"



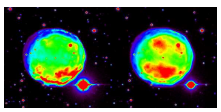
PN G257.5+00.6 (298" x 298")
cuts: upper images 0:1200, middle 0:450, lower 0:100
most amorphous PN with two lobes that have point symmetric extensions; further out, there are many faint nebulosities, filaments, and loops
star 1: H α image (top), center (of hole)
star 2: 15" to the S-E of star 1, next to the inner edge of the [O III] blob
in the S-W quadrant (lower images), nebula emission is detected 225" to the West, 310" to the South, thus we estimate $d_{\rm WE} > 400$", $d_{\rm NS} > 500$"



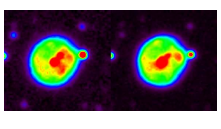
PN G277.1−03.8 (241" x 241")
cuts: upper images 0:20000, lower 0:200
non-circular PN with two lobes, reminds of torus seen in the equatorial plane, with large lobes of diffuse emission at the poles; the tubular shape is not straight, but has a kink $d_{\rm WE}$= 239", $d_{\rm NS}$=155"



PN G283.6+25.3 (241" x 241")
circular PN with two lobes, no central hole, $d_{\rm WE}$= 199", $d_{\rm NS}$=196"



PN G293.6+10.6 (147" x 147")
circular PN with weak lobes, no central hole, distinct secondary shell just outside the main nebula, $d_{\rm WE}$= 94", $d_{\rm NS}$=91"



PN G324.1+09.0 (37" x 37")
circular PN, no central hole , $d_{\rm WE}$= 24", $d_{\rm NS}$=27"

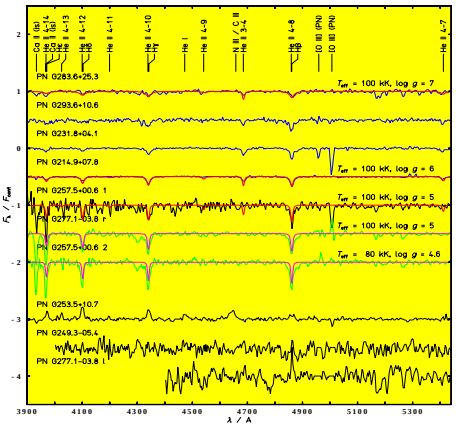


Fig. 1. Spectra of the central stars of the PN from Tab. 1. The positions of identified lines are marked. Note that only in the top four spectra He II λ 4686 Å is clearly detectable (—). In the spectra of PN G277.1−03.8 r and PN G257.5+00.6 2 (—), no H II line can be detected. Synthetic spectra with $T_{\rm eff}=100$ kK and $\log g = 7$, 6, 5 (H + He at solar abundances —), and $T_{\rm eff}=100$, 80 kK and $\log g = 5$, 4.6 (pure H — can only give an impression of the surface gravity g — within a large range of $T_{\rm eff}$ ($\pm$ 40kK), we achieve almost the same line profiles at this resolution. In the case of PN G277.1−03.8, l(eft) + r(ight) denote two stars which are very near together at the center of the PN (see its image), for PN G257.5+00.6, 1 + 2 denote two stars as described in the caption of its images. PN G253.5+107 shows the (reflection) spectrum of the binary system.

Results

→ Imaging

- our deep images show that some of the PNe are much larger than previously measured (compare Tab. 1)
- ratio circular : non-circular PN = 6 : 3
- ratio central hole : no hole = 3 : 3 of circular PN
- ansae: 1 object (PN G253.5+10.7)
- outer shells: 1 prominent shell with halo; 1 with extensions, outer loops, etc.; 2 distinct steps in surface brightness near outer edge (PN G214.9+07.8, PN G293.6+10.6)

→ Spectral Analysis

- useful spectra were obtained for six CSPN which are all H-rich:
  - four have approximately a solar He/H ratio (PN G214.9+07.8, PN G231.8+04.1, PN G283.6+25.3, PN G293.6+10.6)
  - two have a He/H ratio lower than solar (no He II line detectable) (PN G257.5+00.6, PN G277.1-03.8)
- PN G257.5+00.6: both stars (1 + 2) show a similar spectrum, 1 has about half the intensity than 2. It is not clear which is the exciting star of the PN. However, on an U image, 2 is much brighter than 1 and thus probably the central star
- PN G277.1-03.8: it is most likely that the right (NE) star of the centered pair (see the image) is the central star, the left has a much lower intensity towards the UV and its spectrum reminds of cooler stars

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