IFU spectroscopy of Southern PNe: VII Photo-ionization modelling of intermediate excitation class objects

A. Ali, M.A. Dopita

1 Department of Astronomy, Faculty of Science, Cairo University, 12613 Giza, Egypt
2 Astronomy Dept, Faculty of Science, King Abdulaziz University, 21589 Jeddah, Saudi Arabia
3 Research School of Astronomy and Astrophysics, Australian National University, Cotter Rd., Weston ACT 2611, Australia

ABSTRACT

We present integral field unit spectroscopic observations of southern Galactic planetary nebulae (PNe), IC 2501, Hen 2-7, and PB 4. The goal of studying these objects together is that, although they have roughly similar intermediate excitation and evolution of central stars (CSs), they display very different evolution in their nebular structure which needs to be understood. The morphologies and ionisation structures of the objects are investigated using a set of emission-line maps representative of the different ionisation zones. We use those in order to construct two-zone self-consistent photoionisation models for each nebula to determine new model-dependent distances, progenitor luminosities, effective temperatures and CS masses. The physical conditions, chemical compositions, and expansion velocities and ages of these nebulae are derived. In Hen 2-7 we discover a strong poleward-directed jet from the presumed binary CS. Oxygen and nitrogen abundances derived from both collisionally excited and recombination lines reveal that PB 4 displays an extreme abundance discrepancy factor, and we present evidence that this is caused by fluorescent pumping of the O II ion by the EUV continuum of an interacting binary CS, rather than by recombination of the O III ion. Both IC 2501 and PB 4 were classified by others as Weak Emission Line Stars (WELS). However, our emission line maps show that their recombination lines are spatially extended in both objects, and are therefore of nebular rather than CS origin. Given that we have found this result in a number of other PNe, this result casts further doubt on the reliability, or even the reality, of the WELS classification.

Key words: plasmas - photoionisation - ISM: abundances - Planetary Nebulae: Individual IC 2501, Hen 2-7, PB 4

1 INTRODUCTION

Photoionisation modelling of planetary nebulae is vital to an understanding of their CSs and their evolution. On one hand, such models enable us to derive reliable abundances especially for elements observed in only one ionisation zone or those which are observed only in weak emission lines, such as the recombination lines of heavy elements. On the other hand, such models enable us to determine the nebular temperature and density in the different nebular ionisation zones. Furthermore, they can provide information on the distance and evolutionary age of the nebula and are necessary to determine the temperature, luminosity, mass, and radius of the CSs. The location of CS on the luminosity-temperature plane overlaid by the H-burning or He-burning post AGB tracks such as those of Vassiliadis & Wood (1994) and/or Miller Bertolami (2016), provide us with the mass of the precursor star, so that the chemical composition can be related directly to the nature of the precursor star. Reviewing the literature, photoionisation modelling of PNe has been carried out by, for example, Henry et al. (2015); Bohigas et al. (2015, 2013), Yuan et al. (2011), Pottasch et al. (2011, 2009), Morisset & Georgiev (2009), Pottasch & Surendiranath (2005), Surendiranath & Pottasch (2008), Surendiranath et al. (2004), Hyung et al. (2004), and Ercolano et al. (2003) but up to now relatively few of these are based on integral field spectroscopy of the full nebula.

Although Weidmann & Gamen (2011) identified ~ 13% of CSs in a sample of slightly over 3000 PNe, the fundamental difficulty in observing the central stars is that they are weak in visible light since most of their radiation is in the ultraviolet range. Furthermore, the observed spectra of these stars are often contaminated with nebular emission which may lead to errors in their classification. Therefore, high resolution spectra integral field unit (IFU) are important
to be able to properly subtract the contaminating nebular mission and to correctly classify the PN central star.

IFU spectroscopy of PNe also provides an excellent opportunity for constructing accurate nebular models. In particular, we can directly compare the global spectrum to a theoretical model using the size, nebular flux and morphology to constrain the distance, the photoionisation structure, and to define the inner and outer boundaries of the nebula. In addition, we can directly compare measured electron temperatures and densities in the different ionisation zones to constrain the pressure distribution within the ionised material.

In this series of papers, our group has provided IFU images, spectra and detailed PNe photoionisation models for a number of southern PNe. To briefly summarise the key results; self-consistent photoionisation and shock models were constructed to interpret the physics of the interacting planetary nebula PNG342.0-0.17 (Ali et al. 2015b). Basurah et al. (2016) introduced self-consistent modelling for a sample of high-excitation non-Type I PNe with supposed weak emission-line central stars, showing these lines to arise in the nebula rather than the central star. A detailed self-consistent model was developed for the compact, young, and low excitation class PN IC 418 using high spectral resolution IFU spectra covering the spectral range 3300-8950Å (Dopita et al. 2017). This model consists of three separate zones: an inner photoionised shock driven by the accelerating stellar wind of the CS, a photoionised nebular shell, and an outer shock in the AGB wind driven by the over-pressure of the strong D-Type ionisation front. Very recently, Dopita et al. (2018) have developed a set of self-consistent radiative shock models to investigate the physical conditions and peculiar chemodynamics of the N-rich fast-moving knots associated with the bipolar PN Hen 2-111.

In this article, we continue our program of obtaining IFU spectra with both high resolution and very high dynamic range and building detailed photoionisation models. Here we study IC 2501, Hen 2-7, and PB 4. These PNe were chosen to be studied together because, although having both very similar excitation classes and luminosities of the central stars, they display remarkably heterogeneous morphologies, possibly related to the binarity or otherwise of their central stars.

A long-slit spectrum of IC 2501 has been obtained by Milinga et al. (2002a) in the spectral range 3600-9600Å with wavelength dispersions of 2.8Å. The plasma diagnostics and abundances determination were given in a companion paper (Milinga et al. 2002b). An echelle spectrum was obtained by Sharpee et al. (2007) to identify emission lines of the s-process elements Br, Kr, Xe, Rb, Ba, and Pb in this nebula. Their spectrum cover the spectral ranges 3280-4700Å and 4590-7580Å at very high resolution (Δ/Δλ = 28,000 and 22,000, respectively). Also, a few krypton lines at [Kr III] 6826Å, [Kr IV] 5346Å, and [Kr IV] 5868Å were detected in the spectrum of IC 2501 by Sterling et al. (2015). In addition to the emission lines in optical band, infrared features at 17.4 and 18.9μm of C60 were detected in IC 2501 (Otsuka et al. 2014). Cuisinier et al. (1996) were obtained long-slit spectra for Hen 2-7 and PB 4 in the wavelength range 3600-7400Å with a spectral resolution of ∼4.0Å. Based on these observations, they derived the physical conditions, ionic abundances and total elemental abundances of both nebulae. Hα+[N II] and [O III] narrow-band images of IC 2501 and PB 4 were presented by Schwarz et al. (1992). Both images reveal circular an elliptical morphologies for IC 2501 and PB 4, respectively. Another set of Hα+[N II] and [O III] images for PB 4 were presented by Corradi et al. (2003) which show a double PN halo. The inner halo is brighter and structured in Hα+[N II] while the outer halo is more asymmetrical and fragmentary. A narrow band image in [N II] filter, with bandpass filter 18Å, was given by Weidmann et al. (2016) for Hen 2-7. The image shows “a well-defined elliptical nebula with a high surface brightness and a prominent central star”.

Peimbert (1978) originally divided PNe into four types according to their chemical composition, spatial and kinematic characteristics. Type I objects are helium and nitrogen rich, Type II intermediate population, Type III high velocity, and Type IV halo population. Type I objects are those satisfy the condition He/H < 0.14 or N/O > 1.0. Subsequently, Peimbert & Torres-Peimbert (1983) relaxed the Type I condition to include all objects with He/H > 0.125 or N/O > 0.5. Later, Maciel & Quireza (1999) considered a more strict condition, defining Type I as those objects have He/H > 0.125 and N/O > 0.5. Members of Type II are characterised by He/H < 0.125 and N/O < 0.5. Fauendez-Abans & Maciel (1987) further subdivided Type II PNe into two types according to their nitrogen abundance. Quireza et al. (2007) re-analysed the Peimbert classes through a statistical study of a large sample of PNe to remove the confusion concerning the objects which cannot be defined as belonging to a single type. They define the limits between the four Peimbert types on the basis of helium and nitrogen abundances, nitrogen to oxygen ratio, the height above the Galactic disk, and the peculiar velocity of each object (see Table 2, Quireza et al. (2007)).

The main objective of this paper is to provide IFU spectra for the Galactic PNe IC 2501, Hen 2-7, and PB 4 at high resolution (R ∼ 7000), to present a detailed spectroscopic and morphological study and to construct self-consistent photoionisation models for these objects. This paper is structured as follows. The observations and data reduction are explained in Section 2. Section 3 provides analysis of the plasma diagnosis while Section 4 is devoted for describing the morphologies, expansion velocities and distances of the sample in addition to the binarity of the PB 4 CS. Section 5 discusses the misclassification of IC 2501 and PB 4 central stars as weak emission-line stars type. The photoionisation modelling of IC 2501, Hen 2-7, and PB 4 are presented in Section 6 and the conclusions are given in Section 7.

2 OBSERVATIONS & DATA REDUCTION

The IFU spectroscopic observations of Hen 2-7, IC 2501, and PB 4 were acquired at 12 January, 4 April, and 6 April 2016, respectively, and cover the wavelength range 3300-8950Å. The observations were obtained with single pointings using the Wide Field Spectrograph (WiFeS) instrument (Dopita et al. 2007, 2010) mounted on the 2.3-m ANU telescope at Siding Spring Observatory. This instrument delivers a field of view of 25 × 38 at a spatial resolution of either 1.0 × 0.5 or 1.0 × 1.0, depending on the binning on the CCD. By using a series of exposures stepped in integration times, a very high
Table 1. The observing log

| Object (PNG number) | No. of frames | Exposure time (s) | Date | Airmass | Standard & telluric stars |
|---------------------|--------------|------------------|------|---------|--------------------------|
| IC 2501 (PN G261.0-05.7) | 8 | 10(2), 20(2), 150(2), 600(2) | 04/04/2016 | 1.19 | HD 111980 & HIP 41423 |
| B7000 & I7000 | 8 | 10(2), 20(2), 150(2), 600(2) | 04/04/2016 | 1.19 | HD 111980 & HIP 41423 |
| U7000 & R7000 | 8 | 10(2), 20(2), 150(2), 600(2) | 04/04/2016 | 1.19 | HD 111980 & HIP 41423 |
| Hen 2-7 (PN G264.2-08.1) | 9 | 10(3), 60(3), 900(3) | 12/01/2016 | 1.10 | HD 031128 & HIP 41423 |
| B7000 & I7000 | 9 | 10(3), 60(3), 900(3) | 12/01/2016 | 1.10 | HD 031128 & HIP 41423 |
| U7000 & R7000 | 9 | 10(3), 60(3), 900(3) | 12/01/2016 | 1.10 | HD 031128 & HIP 41423 |
| Hen 2-7 (PN G264.2-08.1) | 9 | 10(3), 60(3), 900(3) | 12/01/2016 | 1.10 | HD 031128 & HIP 41423 |
| HD 111980 & HIP 41423 | | | | | |
| PB 4 (PN G275.0-04.1) | 5 | 50(3), 1200(2) | 06/04/2016 | 1.09 | HD 111980 & HIP 41423 |
| B7000 & I7000 | 5 | 100(3), 1200(2) | 06/04/2016 | 1.09 | HD 111980 & HIP 41423 |
| U7000 & R7000 | 5 | 100(3), 1200(2) | 06/04/2016 | 1.09 | HD 111980 & HIP 41423 |

Table 2. Integrated $F(\lambda)$ and de-reddened $F_d(\lambda)$ line fluxes (relative to H$\beta$ = 100) for IC 2501, Hen 2-7, and PB 4. The full version of the table is available online. Only a fraction of the table is presented here to draw the attention of the reader to its content.

| A(Å) | Ion | IC 2501 | Hen 2-7 | PB 4 |
|------|-----|---------|---------|------|
|      |     | $F(\lambda)$ | $F_d(\lambda)$ | $F(\lambda)$ | $F_d(\lambda)$ |
| 3724.13 | [S ii] | 2.26 ± 0.23 | 3.07 $^{+0.32}_{-0.38}$ | 39.08 $^{+0.808}_{-0.523}$ | 52.3 ± 3.3 |
| 3726.03 | [O i] | 35.40 ± 1.19 | 46.50 ± 2.60 | 30.19 $^{+1.162}_{-0.48}$ | 40.8 ± 2.9 |
| 3728.82 | [O ii] | 15.47 ± 0.63 | 20.50 ± 1.20 | 1.42 ± 0.117 | 1.91 ± 0.106 |
| 3734.37 | H i | 2.14 ± 0.21 | 2.63 ± 0.30 | 1.92 ± 0.112 | 2.67 $^{+0.229}_{-0.23}$ |
| 3749.49 | O i | 2.43 ± 0.25 | 3.31 $^{+0.35}_{-0.39}$ | 0.18 ± 0.01 | 0.23 $^{+0.018}_{-0.02}$ |
| 3750.15 | H i | 2.43 ± 0.25 | 3.31 $^{+0.35}_{-0.39}$ | 2.83 ± 0.148 | 3.72 $^{+0.26}_{-0.26}$ |
| 3758.87 | [Ne iii] | 3.76 ± 0.39 | 5.37 ± 0.45 | 4.1 ± 0.2 | 5.19 $^{+0.38}_{-0.41}$ |
| 3819.62 | He i | 1.18 ± 0.08 | 1.44 ± 0.12 | 1.15 ± 0.052 | 1.41 $^{+0.10}_{-0.10}$ |
| 3835.39 | H i | 5.07 ± 0.34 | 6.54 ± 0.50 | 5.43 ± 0.088 | 7.12 ± 0.415 |
| 3868.75 | [Ne iii] | 59.65 ± 14.81 | 76.00 ± 19.60 | 79.95 ± 1.312 | 105 ± 6 |

3 PLASMA DIAGNOSIS

3.1 Line fluxes and excitation class

Emission-line fluxes and their uncertainties were measured from the final combined flux-calibrated U, R, and I spectra using the ALFA code (Wesson 2016). The uncertainties are estimated using the noise structure of the residuals. A double check was done using the splot task in the IRAF software.

The computation of the interstellar reddening coefficients and the subsequent plasma diagnoses steps used the Nebular Empirical Abundance Tool (NEAT; Wesson et al. 2016).

Each of these nebulae is fairly compact and fall well within the WiFeS field of view, having angular diameters (in their largest dimension) of 10 arc sec. (IC 2501), 17 arc sec. (Hen 2-7) and 12.5 arc sec. (PB 4). The global spectra of each PN were extracted from the reduced data cubes utilising a circular aperture matched to the observed size of the PN using QFitsView v3.1 software. The spectra from the four gratings U, B, R, and I were combined applying the scombine task of the IRAF software.

The data reduction was carried out using the PyWiFeS pipeline (Childress et al. 2014). The nebular fluxes were calibrated using the STIS spectrophotometric standard stars HD 111980 and HD 031128. The wavelength scale was calibrated using observations of the Ne-Ar arc Lamp throughout the night. Furthermore, a telluric standard star HIP 41423 was employed to improve the removal of the OH and H$_2$O telluric absorption features in the red. The separation of these features by molecular species allows for a more accurate telluric correction by accounting for night to night variations in the column density of these two species. For further details on this process, please refer to Childress et al. (2014).

Each of these nebulae is fairly compact and fall well within the WiFeS field of view, having angular diameters (in their largest dimension) of 10 arc sec. (IC 2501), 17 arc sec. (Hen 2-7) and 12.5 arc sec. (PB 4). The global spectra of each PN were extracted from the reduced data cubes utilising a circular aperture matched to the observed size of the PN using QFitsView v3.1 software. The spectra from the four gratings U, B, R, and I were combined applying the scombine task of the IRAF software.

3 PLASMA DIAGNOSIS

3.1 Line fluxes and excitation class

Emission-line fluxes and their uncertainties were measured from the final combined flux-calibrated U, R, and I spectra using the ALFA code (Wesson 2016). The uncertainties are estimated using the noise structure of the residuals. A double check was done using the splot task in the IRAF software.

The computation of the interstellar reddening coefficients and the subsequent plasma diagnoses steps used the Nebular Empirical Abundance Tool (NEAT; Wesson et al. 2016).
The line fluxes were treated for the reddening effect applying the extinction law of Howarth (1983). The reddening coefficient $c(H\beta)$ was determined from the weighted mean ratios of the Hydrogen Balmer lines H$\alpha$, H$\beta$, H$\gamma$, and H$\delta$ in an iterative method, assuming Case B at $T_e = 10^4$K.

The observed and de-reddened line fluxes and their uncertainties are given in Table 2.

The HeII $\lambda 4686$/H$\beta$ line ratio probably provides the best estimator for the nebular excitation class (EC). Here, we applied the scheme of Reid & Parker (2010) to determine the EC of IC 2501, Hen 2-7, and PB 4. The He II $\lambda 4686$ line is marginally present in both IC 2501 and Hen 2-7. All three of these PNe are of intermediate EC class (EC $\sim 6$). This result is compatible with the absence of high excitation lines, such as [Ar V] and [Ne V], in the spectra.

The systemic velocity $RV_{sys}$ of the sample was determined using the IRAF external package RVSAO (emssa task), from numerous nebular emission lines. The heliocentric radial velocity $RV_{hel}$ was calculated by correcting the $RV_{sys}$ for the effect of Earth’s motion. The results of IC 2501 and Hen 2-7 reveal good agreement with those of Durand et al. (1998). It appears that there are no previous measurements for the radial velocity of PB 4.

Table 3 lists the H$\alpha$ and H$\beta$ integrated fluxes, $c(H\beta)$, EC, $RV_{hel}$ and distance (Section 4.4) of each PN. Almost all measurements are well consistent with those in the literature.

### 3.2 Temperatures and densities from CELs

The electron temperatures and densities for IC 2501, Hen 2-7, and PB 4 are calculated from their collisional excitation lines (CELs) using the NEAT code. The emission lines which are detected in the PNe spectra allow us to measure both electron temperatures and densities for several stages of ionisation. The nebular temperatures are determined from the line ratios $[O III]$ ($\lambda 4959 + \lambda 5007)/\lambda 4363$, [Ar III] ($\lambda 7135 + \lambda 7751)/\lambda 5192$, [N II] ($\lambda 6548 + \lambda 6584)/\lambda 5754$, [S II] ($\lambda 6717 + \lambda 6731)/\lambda 5200 + \lambda 5730$, [O II] ($\lambda 7319 + \lambda 7330)/\lambda 5726 + \lambda 3729$, and [O I] ($\lambda 6363 + \lambda 6300)/\lambda 5577$ while nebular densities were determined from the line ratios $[O II]$ $\lambda 3727/\lambda 3729$, [S II] $\lambda 6716/\lambda 6731$, [Cl III] $\lambda 5517/\lambda 5537$, and [Ar IV] $\lambda 4711/\lambda 4740$. In Table 4, we list the temperatures and densities of IC 2501, Hen 2-7, and PB 4, and compare these values with those available in the literature and with those derived from their photoionisation models presented in Section 6, below. There is generally good agreement between the literature values and those presented here.

### 3.3 Temperatures and densities from ORLs

The PNe spectra declare few optical recombination lines (ORLs), convenient for electron temperature and density diagnostics. The temperatures were derived from the diagnostic ratios of He I $5876/\lambda 4471$, 6678/4471, 6678/5876, and 7281/5876, and O II $4649/4591$, 4649/4189, and 4649/4089. Further, the densities were derived from the diagnostic ratios of O II $4649/4662$ and 4076/4070 and N II $5679/5666$. The average temperature and density that determined from each ion were listed in Table 4, providing the diagnostic lines are available in the nebular spectra.

Jointly with the temperatures and densities derived from both CELs and ORLs, Table 4 also gives the Paschen jump temperature and the Paschen decrement density applying the NEAT code. We ignored here the Balmer jump temperature and the Balmer decrement density due to the S/N is too low in the UV spectral region of the three nebulae.

Rubin (1986) has examined the effects of the recombination processes in addition to the collisional excitations on the energy level populations of species e.g. nitrogen and oxygen. The recombination contributions of $N^{2+}$ and $O^{2+}$ in the strength of the auroral [N II] $\lambda 5754$ and the [O II] $\lambda 7320$, 7330 lines were estimated following Equations 1 and 3 of Liu et al. (2000), respectively. For the [N II] weak line $\lambda 5754$, we estimate recombination contribution of 4% and 70% of the observed intensity of $\lambda 5754$ in IC 2501 and PB 4, respectively. For the [O II] line $\lambda 7320, 7330$, we estimate recombination contribution of 4% and 65% in the observed intensity of $\lambda 7320$, 7330 in IC 2501 and PB 4, respectively. It is apparent the high contribution of the recombination in the strength of lines $\lambda 5754$ and $\lambda 7320, 7330$ in case of PB 4 compared to IC 2501. This result has a significant effect on the temperatures of PB 4 which derived from both [N II] and [O II] line ratios. Subtracting the recombination contribution, we obtain a temperatures of 9500K from corrected [N II] ($\lambda 6548 + \lambda 6584)/\lambda 5754$ line ratio and 17600K from corrected [O II] ($\lambda 7319 + \lambda 7330)/($\lambda 3726 + \lambda 3729$) line ratio.

### 3.4 Ionic and elemental abundances

In Table 6 we present the ionic and elemental abundances of IC 2501, Hen 2-7, and PB 4 as derived using the NEAT code. The ionic abundances of nitrogen, oxygen, neon, argon, sulphur, and chlorine are derived from the CELs, while helium and carbon are calculated from the optical recombination lines (ORLs) using the appropriate temperature and density for their ionisation zone. When several lines are observed for the same ion the average abundance was adopted. The total elemental abundances were determined from the ionic abundances applying the ionisation correction factors (ICFs) given by Delgado-Inglada et al. (2014). Following the Peimbert classification scheme of PNe as modified by Quireza et al. (2007), none of the three nebulae studied here are of Type I. We classify IC 2501 as of Type IIa, Hen 2-7 as Type IIb, and PB 4 as Type IIb/III.

The oxygen and nitrogen ionic and total abundances in IC 2501 and PB 4 are also computed using the ORLs. The O II abundance of IC 2501 was determined from V1, V5, V10, V19, V28, and V48 multiplets, which mostly agree with each other excepting multiplets V5 and V28 which give higher values. We used the remaining multiplets (V1, V10, V19, and V48) to compute the fractional and overall oxygen abundance. The N II abundance of IC 2501 was determined from V3, V5, and V20 multiplets. We ignored a few blended lines in these multiplets, which gave higher abundance compared to other components. The abundance of each multiplet was computed from a flux weighted average of its components and the overall abundance are determined as the average of the multiplet abundances.
Table 3. Reddening coefficient, observed Hβ flux, observed Hα flux, excitation class, heliocentric radial velocity and distance of IC 2501, Hen 2-7, and PB 4.

| Object   | $c(H\beta)$ | Others | Log F($H\beta$) | Others | Log F($H\alpha$) | Others | EC | RV$_{hel}$ (km/s) | Distance (kpc) |
|----------|--------------|--------|-----------------|--------|-----------------|--------|----|-----------------|---------------|
| IC 2501  | 0.546        | 0.411  | -0.10           | -0.53  | 1.67            | -0.10  | 6.2 | 26.9±1.2        | 2.40          |
| Hen 2-7  | 0.496        | 0.315  | -0.11           | -0.66  | 1.57            | -0.12  | 6.1 | 85.8±2.1        | 2.90          |
| PB 4     | 0.738        | 0.706  | -0.17           | -0.53  | 1.75            | -0.10  | 6.8 | 92.3±2.6        | 3.14          |

Dist 1 & Dist 2 are derived following Ali et al. (2015a) and Frew et al. (2016) distance scales.

* This value is calculated following the Frew et al. (2016) distance equation for optically thin planetary nebulae.

In the case of PB 4, we calculate the OII abundance from V1, V10, V28, and V92 multiplets, which display very good agreement with each other, and the NII abundance determined only from N II lines. The nebula displays a featureless roughly elliptical shape with a fainter outer

The derived adf of oxygen in case of PB 4 is to be more trusted than that of nitrogen. The reason for this is that the ORL nitrogen abundance is determined mainly from N$^+$ abundance while the nitrogen abundance from the CELs is determined only from N$^+$ lines and relies heavily on the estimated on the ICF. This becomes particularly uncertain for CELs where a small amount of nitrogen (~16%) is in the form of N$^+$. The result of high O adf joins PB 4 to the group of PNe with extreme adfs (adf $> 10$, Wesson et al. (2018)).
emission-line maps of IC 2501 in three different ions: [S III] at 6312 Å (left panel), [S II] at 6730 Å (middle panel), and [Ne III] at 3868 Å (right panel). The rough elliptical morphology are seen in all maps, with indication to double shells clearly seen in [Ne III] and [S II] images. The emission of the outer shell is slightly higher than the background sky emission. The North is to the top of the image and East is to the left.

Table 5. Fractional ionic abundances of O\(^{2+}\) and N\(^{2+}\) lines in IC 2501 and PB 4.

| λ(Å) | Multiplet | \(N^{+}/H^{+}\) | λ(Å) | Multiplet | \(N^{+}/H^{+}\) |
|------|-----------|-----------------|------|-----------|-----------------|
| IC2501 | | | | |
| O\(^{2+}/H^{+}\) | | | N\(^{2+}/H^{+}\) | | |
| 4649.13 | V1 | 5.30E-03 (±1.80E-04) | 5666.63 | V1 | 1.49E-03 (±1.30E-04) |
| 4661.63 | V1 | 4.43E-04 (±2.00E-04) | 5679.02 | V1 | 1.44E-03 (±1.30E-04) |
| 4414.90 | V5 | 5.75E-04 (±1.70E-04) | 5710.77 | V3 | 2.37E-04 (±3.00E-05) |
| 4416.97 | V5 | 1.08E-04 (±2.00E-04) | | | |
| 4437.27 | V5 | 1.35E-04 (±2.00E-04) | | | |
| 4072.16 | V10 | 1.84E-04 (±3.00E-05) | 4788.13 | V20 | 2.27E-04 (±3.00E-05) |
| 4132.89 | V19 | 5.75E-04 (±6.00E-05) | | | |
| 4153.90 | V19 | 7.75E-04 (±7.00E-05) | | | |
| 4153.90 | V19 | 7.20E-04 (±7.00E-05) | | | |
| 4190.86 | V28 | 1.98E-04 (±1.00E-04) | | | |
| 4068.83 | V28 | 1.15E-04 (±7.00E-04) | | | |
| 4068.83 | V28 | 1.34E-04 (±7.00E-04) | | | |
| 4088.29 | V48a | 4.56E-04 (±6.00E-05) | | | |
| 4088.29 | V48a | 4.50E-04 (±6.00E-05) | | | |
| 4088.29 | V48a | 5.60E-04 (±5.00E-05) | | | |
| O\(^{2+}/H^{+}\) | | | N\(^{2+}/H^{+}\) | | |
| 4641.81 | V1 | 5.30E-03 (±8.00E-04) | 5668.63 | V1 | 1.49E-03 (±1.30E-04) |
| 4661.63 | V1 | 4.43E-04 (±2.00E-04) | 5679.02 | V1 | 1.44E-03 (±1.30E-04) |
| 4414.90 | V5 | 5.75E-04 (±1.70E-04) | 5710.77 | V3 | 2.37E-04 (±3.00E-05) |
| 4416.97 | V5 | 1.08E-04 (±2.00E-04) | | | |
| 4437.27 | V5 | 1.35E-04 (±2.00E-04) | | | |
| 4072.16 | V10 | 1.84E-04 (±3.00E-05) | 4788.13 | V20 | 2.27E-04 (±3.00E-05) |
| 4132.89 | V19 | 5.75E-04 (±6.00E-05) | | | |
| 4153.90 | V19 | 7.75E-04 (±7.00E-05) | | | |
| 4153.90 | V19 | 7.20E-04 (±7.00E-05) | | | |
| 4190.86 | V28 | 1.98E-04 (±1.00E-04) | | | |
| 4068.83 | V28 | 1.15E-04 (±7.00E-04) | | | |
| 4068.83 | V28 | 1.34E-04 (±7.00E-04) | | | |
| 4088.29 | V48a | 4.56E-04 (±6.00E-05) | | | |
| 4088.29 | V48a | 4.50E-04 (±6.00E-05) | | | |
| 4088.29 | V48a | 5.60E-04 (±5.00E-05) | | | |

The [Fe III] emission-line map is remarkable, showing a jet-like morphology with point-symmetric condensations of emissions along the polar axis. Purely from the point of view of photoionisation theory, the morphology of [Fe III] should be similar to that of [O II], since the ionisation potential of [Fe II] is 16.19 eV, that of [Fe III] is 30.65 eV while the ionisation potential of [O I] is 13.62 eV and that of [O II] is 35.12 eV. The great difference of morphology between the [Fe III] and [O II] emission can only be explained by invoking a jet, either excited through shocks in a jet, or in a mass-loaded polar-directed stellar wind. The idea that the [Fe III] emission arises in a jet is confirmed by the kinematics, since relative to the systemic velocity, the SE jet is approaching at +51 ± 5 km/s at its tip, while the NW jet is receding at −44 ± 5 km/s. The strength of the [Fe III] emission in the jets strongly suggests that the Fe-containing dust has been destroyed within them. This points to the origin of the outflowing gas being close to the CS, within the dust sublimation radius, suggestive of a mass-loaded outflow from an interacting binary CS.

Figure 3 displays the morphology of PB 4 nebula in five different emission-line maps and one composite RGB colour image. In general, the object shows an elliptical morphology, except O II map, with two symmetric maximum of brightness along the minor axis (like a barrel with open ends) in the H\(_\alpha\), [O II], and [O III] maps. In the [N II] emission-line map, the nebula has an elliptical ring-like shape with two symmetric knots, in yellow colour, located at the ends of the shell visible in the green and blue colours. The outer shell is only marginally distinguishable from the background sky emission.

Figure 2 displays three surprisingly different morphologies of the Hen 2-7 nebula in six emission-line maps. This shows a butterfly shape with an equatorial density enhancement forming a dense torus of gas around the CS, best seen in the [N II], [S II], and [O II] lines. The two lobes are oriented at \(PA \sim 120^\circ\) with somewhat brighter emission in SE lobe compared to NW lobe. The object shows an elliptical morphology in the [O III] and He II emission lines with a roughly round central dense emission. In general, the surface brightness decreases in both maps from the centre to the outer boundary.
nebular major axis. The [SII]-He-I-[SIII] composite colour image of PB 4 shows the same morphology that is seen in the [NII], with the two symmetric knots which appear in magenta in the (B+R) colour image.

4.2 Does PB 4 host a close binary central star?

Corradi et al. (2015) have reported a possible relation between the largest adfs and the CS binarity of PNe. They studied three nebulae (A 46, A 63, and Ou 5) with a post-common-envelope binary star. A 46, and Ou 5 show O\(^{2+}/\)H+ adfs larger than 50, and this range as high as 300 in the inner regions of A 46. A 63 shows a smaller adf around 10. Jones et al. (2015, 2016) have strengthened the case for a correlation between elevated or extreme adfs and CS binarity in PNe through their study of Hen 2-155, Hen 2-161, and NGC 6778. Sowicka et al. (2017) suggested a possible correlation between low adfs and intermediate-period post-common-envelope CSs. Very recently Wesson et al. (2018) confirmed the link between CS binarity and extreme adfs in PNe. They presented deep spectra for seven PNe host close binary CSs and found a several of them with extreme adfs. Further they analysed a small statistical sample of 15 PNe showing elevated or extreme adfs and found no link between CS surface chemistry and nebular discrepancy, but a clear link between binarity and the abundance discrepancy. Their analysis also revealed an anti-correlation between abundance discrepancy and nebular electron densities. Furthermore this study discovered that the PNe with binary CSs of a period <1.15 d have adfs exceeding 10, and an electron density
Figure 2. The emission-line maps of Hen 2-7 nebula in six different ions: [N II] at 6548 Å (upper left panel), [S II] at 6730 Å (upper middle panel), and [O II] at 3729 Å (upper right panel), [Fe III] at 4658 Å (lower left panel), [He II] at 4686 Å (lower middle panel), and [O III] at 5007 Å (lower right panel). In this figure and subsequent figures, North is at the right of the image and East is to the top. A butterfly morphology appears in the low ionisation lines of nitrogen, sulphur, and oxygen. A pronounced dense tours of gas appears mainly in yellow colour mixed with less emission in green colour. By contrast with the butterfly morphology, Hen 2-7 has an elliptical appearance in both the He II and [O III] emission lines, while the [Fe III] emission-line map shows a jet-like morphology with obvious two symmetric condensations of gas along the major (polar) axis.

less than $\sim 1000 \text{ cm}^{-3}$ while the longer period binaries have $\text{adfs} < 10$ and much higher densities. Thus they conclude that the adf can be used as a trusted tool in identifying the presence of a binary CS. We might speculate that this is because the UV spectrum of the companion star induces strong fluorescent pumping of the recombination lines, as found in the case of the relatively cool central star of IC 418 by Morisset & Georgiev (2009). Other possible explanations are discussed below.

The CS of PB 4 nebula was classified as a true WELS type Weidmann et al. (2015), but we proved her this classification is erroneous (see Section 5) due to most WELS feature lines arise in the nebula. Miszalski et al. (2011) and references therein, pointed out that many of the characteristic WELS emission lines are observed in close binary CSs of PNe. Based on the morphology of a sample of 458 PNe, Soker (1997) introduced a classification scheme to characterize the evolution of binary progenitors of PNe. The basis of the classification is that axisymmetrical, bipolar, and elliptical PNe morphology arise from axisymmetrical mass loss from progenitor star as a result of the interaction of the progenitors with binary companion where the companion can be stellar or substellar (brown dwarfs or planets). According to this scheme, the progenitor star of PB 4 was classified (with low confidence) as a progenitor which is interacting with substellar companion.

Our results show that PB 4 nebula has a particularly strong recombination line spectrum (Table 2) with de-reddened line fluxes of 6.1, 3.2, and 2.2 for $\text{C II} \lambda 4267.15$, $\text{N III} \lambda 4640.64$, and $\text{O II} \lambda 4649.13$ on the scale of $\text{F(H}\beta) = 100$, respectively. A comparison between the oxy-
gen and nitrogen abundances computed from the ORLs and CELs, confirms that PB 4 displays an extreme adf.

The map in O II line at $\lambda 4649.13$ (Figure 3) shows that the spatial distribution of $O^{2+}$ recombination emission roughly matches those of $C^{2+} \lambda 4267.15$ and $N^{3+} \lambda 4640.64$, despite the much lower signal to noise in these other ions (Figure 4). However, the O II $\lambda 4649.13$ map has a spatial distribution which is remarkably different than that of the supposed parent ion emitting in the [O III] $\lambda 5006.84$ CEL for which the emission is distributed through the entire object (Figure 3). A similar result was achieved by García-Rojas et al. (2016) where they found the O II ORL emission in NGC 6678 is concentrated inside the [O III] CEL emission or H I emission. Paradoxically, the O II $\lambda 4649.13$ map much more closely resembles the [O II] $\lambda 7319.99$ map, strongly suggesting that the O II “recombination” lines do not arise from recombination at all, but from fluorescent pumping of excited states in the $O^{+}$ ion. The fluorescent path for pumping the O II $\lambda 4649.13$ transition is from the ground state through the UV3 $\lambda 430$ line to the $3d^4P$ state, which can then decay via the V11, V19 and V28 multiplets. The path through the V11 multiplet then decays through the O II $\lambda 4649.13$ line.

In PB4, the fact that the O II $\lambda 4649.13$ and the [O II] $\lambda 7319.99$ maps are extended in the polar direction, while the [N II] $\lambda 6583.5$ map shows only an elliptical ring seems to show that the EUV radiation which is doing the pumping is preferentially directed in the polar direction, suggesting that the central binary is an interacting system, which would be consistent with a short-period binary CS, according with the conclusions of the Wesson et al. (2018) study. The presence of a fairly hot binary companion is further suggested by the relatively strong continuum emission seen in our spectra. Apart from the NaD interstellar absorption lines, this spectrum is featureless. This enhanced stellar continuum results in the derivation of a very low Zanstra Temperature
of 46000 K (Gleizes et al. 1989), while our photoionisation modelling (presented below) results in a stellar effective temperature $T_{\text{eff}} = 93000 \pm 3000$ K.

In conclusion, we infer that the CS of PB 4 is almost certainly an interacting binary with a sub-dwarf O-type companion, and that a poleward directed EUV continuum produced in the interaction is fluorescently pumping excited states in the O$^+$ ion to produce the extreme adf seen in the polar regions of this object. However, a photometric variability study and spectroscopic radial velocity observations would be essential to confirm the binary nature of the central star.

### 4.3 Expansion velocities

The expansion velocities of the sample were measured, following Gieseking et al. (1986), from a number of emission lines of different ionisation levels. The ionisation potential (IP) of each emission line is presented alongside the expansion velocity (V$_{exp}$) in Table 7. It is obvious from the results that there is a general trend for increasing expansion velocity with decreasing the ionisation potential, as would be expected from the ionisation stratification of these nebulae.

reviewing the literature, no measurements are found for IC 2501 and PB 4. Hen 2-7 has three velocity measurements of 15.3, 18.3, and <6 km/s derived from [O III], [O II] and He II emission lines, respectively (Meatheringham et al. 1988). The uncertainties in the previous values were not calculated by the authors but they reveal a statistical errors of $\sim 10\%$ in the measurements of the full width at half-maximum. Our velocity measurements of Hen 2-7 (Table 7) indicate higher values compared with those given by Meatheringham et al. (1988). This could be attributed to the different spectral resolution and the different spectroscopic techniques which have been employed.

### 4.4 Distances

None of IC 2501, Hen 2-7, and PB 4 has a reliable individual distance based upon trigonometric parallax, spectroscopic parallax of the CS, cluster membership, or angular expansion distances. Therefore, we must rely here on the statistical distance methods. We adopted the average distance deduced from the two recent statistical distance scales of Frew et al. (2016) and Ali et al. (2015a). The results are given in Table 3.

The detailed photoionisation modelling is capable of providing an independent distance estimate, as discussed in Basurah et al. (2016). Based upon these, improved distance estimates are presented below.

### 5 MISCLASSIFICATION OF THE IC 2501 AND PB 4 CENTRAL STARS

Through the analysis of $\sim 80$ emission-line CSs, Tylenda et al. (1993) found that about half belong to the [WR] star class while others display emission lines at the same wavelengths as [WR] stars but having narrower line widths and weaker line intensities. They termed the latter group Weak Emission Line Stars (WELS). The spectral lines which characterise the WELS class are the recombination lines of C and N. These lines are N III $\lambda$4634, 4641, C III $\lambda$4650, C IV $\lambda$4658, and C IV $\lambda$$\lambda$5801, 5812. The emission line of C III $\lambda$5696 is either very weak or absent.

It is hard to discriminate the width of these lines from the nebular lines, although on low dispersion spectra the group of lines around 4650Å and the C IV doublet around 5805Å may appear somewhat broader. Miszalski (2009) claimed that many of WELS are likely to be misclassified close binaries. Further, Miszalski et al. (2011) indicated that many of the characteristic WELS emission lines have been observed in close binary central stars of PNe and originate from the irradiated zone on the side of the companion facing the primary. Basurah et al. (2016) discovered that, for few objects, the WELS classification may well be spurious, since the WELS features originated in the nebula, rather than in the central star. Additionally, in Ali et al. (2016), we successfully extracted the CS spectrum of the M3-6 nebula from its 3-D data cube. On the basis of the observed CS spectral lines, we re-classified it as a hydrogen rich star of spectral type O3 I(f$^*$) rather than its prior WELS type.

The appearance of the proposed WELS features in the low dispersion (3.4 Å/pixel) CSs spectra of IC 2501 and PB 4 encouraged Weidmann & Gamen (2011) and Weidmann et al. (2015) to classify both CSs as probable WELS and true WELS types, respectively. Very recently, Weidmann et al. (2018) re-classified the CS of IC 2501 as O-type star. Further, they suggested that the CS could be a binary system due to the presence of a shift between the nebular emission lines and their corresponding stellar features. This result supports the above conclusion that most weak emission-line stars are indeed close binary stars. Inspecting the literature, the CS of Hen 2-7 was not detected yet.

Unfortunately we are unable to extract the CS spectra at adequate S/N for any of this PNe sample from their data cubes, but it is clear that the WELS classification for IC 2501 and PB 4 are erroneous for these nebulae. In Figure 4, we present emission-line maps of IC 2501, Hen 2-7, and PB 4 in two proposed CS recombination lines of WELS type. It is obvious that the emission of both lines are spatially distributed over a large nebular area, therefore they are of nebular rather than CS origin.

### 6 SELF-CONSISTENT PHOTOIONISATION MODELLING

The details of our self-consistent photoionisation modelling have been adequately presented in our earlier papers (Basurah et al. 2016; Dopita et al. 2017), so we will only present a brief summary here. For the photoionisation modelling we use Mappings V version 5.1.12 code (Sutherland & Dopita 2017). For the UV spectrum of the central star, we use the model atmospheres from Rauch (2003). We assume that heavy elements are depleted onto dust. For the initial depletion factors we use the Jenkins (2009) scheme, with a base depletion of Fe of -1.00 dex, but these are adjusted by individual element to best fit the observations. We allow for

\begin{table}
\centering
\begin{tabular}{|c|c|c|}
\hline
Element & Initial Depletion & Adjusted Depletion \\
\hline
Fe & -1.00 & -1.00 \\
\hline
\end{tabular}
\end{table}

\footnote{Available at https://miocene.anu.edu.au/mappings}
Table 7. Measured expansion velocities of IC 2501, Hen 2-7, and PB 4.

| Ion     | λ (Å)   | IP     | V_{exp} (km/s) |
|---------|---------|--------|----------------|
| [Ne III] | 3868 & 3967 | 63.45  | 21.50          | 17.90          |
| [Ar IV]  | 4740    | 59.81  | 21.30          | 17.30          |
| [O III]  | 4959 & 5007 | 54.93  | 22.00          | 18.64          |
| [Cl IV]  | 7530    | 53.46  | 22.10          | 17.11          |
| [Ar III] | 5191 (7751) | 40.74  | 24.98          | 18.90          |
| [Cl III] | 5517 & 5537 | 39.61  | 31.09          | 18.35          |
| [O II]   | 3727 & 3729 | 35.12  | 31.40          | 19.36          |
| [N II]   | 6548 & 6583 | 29.6   | 32.30          | 18.55          |
| [S II]   | 6716 & 6731 | 23.33  | 30.79          | 18.70          |
| [N I]    | 5197 & 5200 | 14.53  | 34.00          | 18.70          |
| [O I]    | 6300 & 6363 | 13.62  | 33.10          | 18.70          |

Average 15.10 27.20 18.43

Figure 4. This figure shows the emission-line maps of IC 2501 (left upper and lower panels), Hen 2-7 (middle upper and lower panels), and PB 4 (right upper and lower panels) in the optical recombination lines C II (upper panels), and N III (lower panels). Both lines are supposed to be of central star origin according to the WELS classification. However, it is obvious the emissions of both lines are spatially extended in all objects, and therefore of nebular rather than CS origin.
both grain charging, and photoelectron emission, which can be an important heating process in these nebulae (Dopita & Sutherland 2000).

Our object is to use the de-reddened integrated global spectrum of the PNe to build a model which optimises the fit to a many of the observed emission lines as possible, while being consistent with the morphological properties of the nebula. This optimisation is done by minimising the L1-norm for the fit. That is to say that we measure the modulus of the mean logarithmic difference in flux (relative to Hβ) between the model and the observations viz.,

$$L_1 = \frac{1}{m} \sum_{n=1}^{m} \left| \frac{F_n(\text{model})}{F_n(\text{obs.})} \right|$$

This procedure weighs fainter lines equally with stronger lines, and is therefore more sensitive to the values of the input parameters.

At the same time, we seek to match both the observed physical size and the absolute Hβ flux, assisted by the physical appearance and structure of the nebula in the IFU emission line images. In general, the models consist of an optically thick component (in which lines such as [O I], [O II], [N I], [N II], and [S II] mostly arise), as well as an optically-thin component which gives rise to emission lines of HeII [O III], [Ne III], [Ar IV] as well as lines of higher ionisation stages for the various ions observed.

The pressure in the ionised plasma is determined by the density sensitivity of the central star, and the Hβ flux (which constrains the luminosity of the central star, $L_*$), we adjust the abundances of individual elements in order to provide an optimum fit for all observed ionisation stages of each element.

We now describe the detailed photoionisation fitting to each nebula.

### 6.1 IC 2501

The images of IC 2501 in Figure ?? show a smooth featureless elliptical shell. From the strength of the [O I] doublet λ6300, 6363 it is evident that this nebula is optically thick. We have therefore modelled this nebula as a single optically-thick shell with a mean radius equal to the average of the major and minor axes. At the assumed distance of 2.64 kpc, this corresponds to a radius of $1.55 \times 10^{17}$ cm.

Given that the nebula is optically-thick, the extreme weakness of the HeII λ4686 line provides a tight constraint on the stellar effective temperature, $50 < T_{\text{eff}} < 60$ K. The detailed model fit gives $T_{\text{eff}} = 55 \pm 3$ K with an inner ionisation parameter $\log U_{\text{in}} = -2.15$, corresponding to a nebular inner radius of $1.0 \times 10^{17}$ cm. The stellar luminosity is $L_* = (1.15 \pm 0.2) \times 10^{37}$ erg/s, or $2990 \pm 520 ~L_\odot$.

The full photoionisation model parameters for this and the other nebulae are given in Table 8, and the derived chemical abundance sets are listed in Table 5. The abundances given here are the gas phase abundances, and do not include the fraction of the heavy elements trapped in grains. To estimate the total (gas + solid phase) abundances, one should multiply the abundances listed in Table 5 by the following factors: He 1.00, C 1.32, N 1.00, O 1.05, Ne 1.00, Ar 1.00 and Cl 1.00. Table 4 gives the modelled temperatures and densities for the various ions observed.

### 6.2 He2-7

This nebula presents more of a challenge to model, thanks to its “butterfly” structure, and the evidence presented in Section 4.1 that it is powered by a strong bipolar outflow. In this object we treat the equatorial ring as one region, and the bipolar structure as a second region. These two regions have quite different densities (and hence gas pressures). This is clearly shown by a map of the density-sensitive ratio; [S II]λ6717/λ6731, presented in Figure 6. This map was prepared by extracting the individual line images using QTFitsView as .fits files, using the iraf imrepl task to trim the [S II]λ6731 image to remove noisy pixels, and then dividing one image by the other using the imarith task.

**Figure 5.** The geometry of our detailed photo-ionisation model. The diagram represents a slice through the mid-plane of the nebula, which has rotational symmetry. The optically-thick portion is therefore a torus in the equatorial plane.
From Figure 6 we deduce that the nebula can be modelled as an inner ellipse of radius 5.5 arc sec., and an electron density of $1050 \pm 130 \text{ cm}^{-3}$, while the outer butterfly wings at $PA \sim 120^\circ$ have a radius of 9.5 arc sec. and a mean electron density of $400 \pm 100 \text{ cm}^{-3}$. Again the He II line strength provides a good constraint on the stellar effective temperature: $T_{\text{eff}} = 83.5 \pm 1.5 \text{kK}$.

In order to determine the luminosity, we used the procedure described in Basurah et al. (2016) by varying the assumed distance to obtain a simultaneous fit for the nebular radius in the two zones of the model, as well as the absolute $H\beta$ flux. This procedure yields a somewhat larger L1-norm of the fit, the $H\beta$ flux is predicted to be $log L_{H\beta} = 34.35$, vs the observed value (at an assumed distance of $4.3 \text{ kpc}$) of $log L_{H\beta} = 34.3$. The implied luminosity of the central star is $L_* = (4.5 \pm 1.1) \times 10^{36} \text{ erg/s}$, or $1175 \pm 300 L_\odot$.

### Table 8. Photoionisation model parameters for IC 2501, Hen 2-7, and PB 4.

| Nebula | Parameter | Value |
|--------|-----------|-------|
| IC 2501 | Stellar Luminosity, $L_*$ | $2990 \pm 520 L_\odot$ |
| | Stellar Effective Temperature, $T_{\text{eff}}$ | $55000 \pm 3000 \text{ K}$ |
| | L1-norm of fit (dex.) | 0.079 |
| | Nebular Pressure, $P/k \text{ (cm}^{-3} \text{ K)}$ | $2.15 \times 10^7$ |
| | Outer Radius @50% HII (cm) | $1.52 \times 10^7$ |
| | Estimated Distance | $4.3 \pm 0.5 \text{kpc}$ |
| | LI-norm of fit (dex.) | 0.045 |
| | Nebular Pressure, $P/k \text{ (cm}^{-3} \text{ K)}$ | $9.0 \times 10^6$ |
| | Outer Radius (cm) | $6.90 \times 10^7$ |
| | Estimated Distance | $3.1 \pm 0.3 \text{kpc}$ |
| He 2-7 | Stellar Luminosity, $L_*$ | $1175 \pm 300 L_\odot$ |
| | Stellar Effective Temperature, $T_{\text{eff}}$ | $83500 \pm 1500 \text{ K}$ |
| | L1-norm of fit (dex.) | 0.090 |
| | Nebular Pressure, $P/k \text{ (cm}^{-3} \text{ K)}$ | $3.0 \times 10^7$ |
| | Outer Radius @50% HII (cm) | $3.86 \times 10^7$ |
| | Estimated Distance | $4.3 \pm 0.5 \text{kpc}$ |
| | LI-norm of fit (dex.) | 0.045 |
| | Nebular Pressure, $P/k \text{ (cm}^{-3} \text{ K)}$ | $9.0 \times 10^6$ |
| | Outer Radius (cm) | $6.90 \times 10^7$ |
| | Estimated Distance | $3.1 \pm 0.3 \text{kpc}$ |
| | LI-norm of fit (dex.) | 0.090 |
| | Nebular Pressure, $P/k \text{ (cm}^{-3} \text{ K)}$ | $2.8 \times 10^7$ |
| | Outer Radius (cm) | $1.9 \times 10^7$ |
| PB 4 | Stellar Luminosity, $L_*$ | $1300 \pm 300 L_\odot$ |
| | Stellar Effective Temperature, $T_{\text{eff}}$ | $93000 \pm 3000 \text{ K}$ |
| | Estimated Distance | $3.1 \pm 0.3 \text{kpc}$ |
| | LI-norm of fit (dex.) | 0.090 |
| | Nebular Pressure, $P/k \text{ (cm}^{-3} \text{ K)}$ | $4.5 \times 10^7$ |
| | Outer Radius @50% HII (cm) | $2.4 \times 10^7$ |
| | Estimated Distance | $3.1 \pm 0.3 \text{kpc}$ |
| | LI-norm of fit (dex.) | 0.090 |
| | Nebular Pressure, $P/k \text{ (cm}^{-3} \text{ K)}$ | $2.8 \times 10^7$ |
| | Outer Radius (cm) | $1.9 \times 10^7$ |

This nebula is quite optically-thin, especially in the polar direction to the main elliptical ring (in which most of the flux is concentrated). However, an inspection of Figure 3 reveals a surprising anomaly. While the [O III] image is very similar to the Hγ image in its morphology, and [N II], as expected is confined to the elliptical ring, the temperature-sensitive [O II] $\lambda 7219.99$ line image brings out the polar extension of the nebula, seen clearly in the high-excitation lines, such as [Ar IV] $\lambda 237.26$ and in the O II $\lambda 4649.13$ transition. On the other hand, the image in the [O II] doublet $\lambda 3727.0, 3728.8$,

---

**Figure 6.** The spatial variation of the density-sensitive [S II] $\lambda 6731/6717$ ratio in He 2-7. It is evident that the elliptical ring is systematically denser than the “butterfly” wings of this bipolar nebula.

**Figure 7.** The spatial variation of the [N II]$\lambda 5754.6/6583.5$ ratio in PB4. The polar axis is characterised by very high electron temperatures, possibly characteristic of a high ionisation parameter, or shock heating by a stellar wind.
although of very poor quality due to the heavy reddening, shows a morphology resembling that of [NII]λ5754.5. This suggests that the plasma in the polar axis (P.A. ~ 160°) is of much higher temperature than that in the elliptical ring.

To investigate this possibility further, we constructed a line ratio image, as described above, in the [NII]λ5754 line. The results show an enhancement of ~ 70% in the strength of the [NII]λ5754 line. This value is reasonable that deduced from the spectrum of the entire nebula (Section 3.3).

Again, we used the procedure described in Basurah et al. (2016) by varying the assumed distance to obtain a simultaneous fit for the nebula radius in the two zones of the model, as well as the absolute Hβ flux. However, in this case, we required a very small optical depth in the H-ionising continuum to fit the polar region (τ = 1.3), and we also require that the elliptical disk is somewhat optically-thin to the escape of H-ionising photons (τ = 10). This procedure gave a distance in good agreement with that given in Table 3; 3.1 ± 0.3 kpc, giving an outer radius of 2.7 × 10^17 cm for the inner ellipse (vs. 2.4 × 10^17 cm given by the model), and 1.9 × 10^17 cm for the butterfly wings, vs. 1.9 × 10^17 cm as predicted by the model. At this distance, the absolute Hβ flux is 1.3 × 10^44 erg/s vs. 1.4 × 10^44 erg/s for the model. The implied stellar luminosity of the central star is L_ν = (5 ± 1) × 10^36 erg/s, or 1300 ± 390 L☉, and the stellar temperature T_H = 93 ± 3.0 kK. The central disc contributes ~ 57% of the total flux.

The L1-norm for the fit is 0.098 dex. This fit is poorer than the other PNe because the strength of the temperature-sensitive lines of [OII], [NII] are underestimated by the model, while the [OIII]λλ4959,5007 cm given in Table 3, 34 cm for the inner ellipse and 36 cm for the butterfly wings, giving a distance to the object of 3.2 × 10^17 cm. This distance can enhance the temperature-sensitive lines.

An alternative explanation for these discrepancies, and for some of the recommbination line abundance anomalies in this object could be that the electron distribution is a k-distribution rather than a Classical Maxwell-Boltzmann distribution in the polar regions of this nebula, as a consequence of mechanical energy transport in the outflow (Nicholls et al. 2012). Recently, Livadiouk (2018) has proved that k-distributions are the most general, physically meaningful, distribution function that particle systems are stabilised into when reaching thermal equilibrium, and that the Classical Maxwell-Boltzmann distribution simply represents a limiting case. As shown by Nicholls et al. (2012), the high energy tail of a k-distribution can enhance the temperature-sensitive collisionally-excited lines, while at the same time the excess of low-energy electrons in the k-distribution enhances the recombination lines.

6.4 Model fits to observations

Overall the photoionisation models described above provide an excellent fit to the observations. In Figure 8 we show both the theoretical model fluxes and the residuals plotted against the observed line fluxes, all on a logarithmic scale. In Table 9 we list the observed fluxes and model fluxes of the lines used in the fitting process. The full observed line list and their observational errors are given in Table 2. Overall the model fits are excellent. However, it is clear that the models system-
6. Inferred progenitor masses and nebular ages

In Figure 9, we show the positions of these objects on the Hertzprung-Russell (H-R) Diagram compared with the tracks for Hydrogen-burning objects from Vassiliadis & Wood (1994), along with the objects which we previously analysed by these techniques (Basurah et al. (2016), Dopita et al. (2017)). The implied mass for the three PNe studied here is $M \sim 1.0 M_\odot$, or less, if these are interpreted as Hydrogen-burning objects. However, it is more likely that they represent higher-mass Helium-burners which are less luminous in this part of the H-R Diagram. If Helium-burning, then these objects have masses in the range $1.0 \lesssim M/M_\odot \lesssim 1.5$. From their expansion velocities we deduce nebular ages of 3200 yr (IC2501), 4500 yr (He 2-7) and 4130 yr (PB 4). These ages would be consistent with $M \sim 1.5 M_\odot$ Helium-burning nuclei (Vassiliadis & Wood 1994).

7 CONCLUSIONS

In this paper, we have analysed three galactic PNe using high-resolution integral field spectroscopy, performed detailed photoionisation analyses using classical ICF techniques, and constructed two-zone photoionisation models to reproduce both the dimensions and the absolute H$\beta$ fluxes of these objects. Although all three objects studied here are almost at the same evolutionary state as far as the PN is concerned, they are strikingly heterogeneous in term of their structure and morphology. One is almost spherical and dense, a second is an elongated bipolar with a strong ionised jet in rapid expansion, and the third has a high-temperature polar conical region with strongly enhanced permitted lines in N II and O II. The calculated oxygen abundance from recombination lines for PB 4 nebula is found to be discrepant by a factor of $\sim 18$ relative to that calculated from collisionally excited lines. This result places PB 4 nebula in the select class of PNe that display extreme abundance discrepancy factors, which Wesson et al. (2018) has identified as possessing short-period interacting binary central stars. From the comparison of the nebula morphology in several ions we suggest that this abundance discrepancy factor is probably in major part due to EUV fluorescence in the O$^+$ ion, rather than as the result of recombination of O$^{2+}$ to O$^+$. In this case, the EUV radiation field from the presumed bi-

Figure 8. (Upper panels: The theoretical model predicted line fluxes plotted against the observed fluxes on a logarithmic scale. Lower panels: the logarithmic residuals of the model fit compared with the observations. The error bars show only the observational uncertainties.

Figure 9. The H-R diagram for the PNe analysed so far, with their measurement error ellipses. The objects from this paper are marked in red. The Hydrogen-burning evolutionary tracks of the central stars of PNe are taken from Vassiliadis & Wood (1994), and are marked according to the initial stellar mass and the age of the PNe. Note that, assuming that the lie on Hydrogen-burning tracks, the implied mass for these objects is $M \sim 1.0 M_\odot$. However, it is more likely that these objects are Helium-burning PNe of higher mass.

Naturally over-estimate [S III]$\lambda$6312, and the [N I]$\lambda$5198, 5200 doublet for reasons that are obscure to us.
nary nucleus appears to be strongly beamed in the poleward direction.

Furthermore, both He2-7 and PB 4 show evidence of a strong polar-directed stellar wind. In the case of He 2-7, we can infer the velocity of outflow from the [Fe III] dynamics, using the ellipticity of the equatorial ring to determine the angle of inclination to the line of sight. This gives $v_\perp \approx 88 \pm 10 \text{ km/s}$. In the case of PB 4, the very high electron temperature deduced from the [NI] lines (which also seems to apply to the [OI]) suggests the operation of shocks at the boundary layer of a polar-directed stellar wind. No such enhancement is seen in the [O III] lines, and additionally, we find no evidence of an enhanced expansion rate in the high-temperature plasma.

ACKNOWLEDGEMENTS

The authors would like to thank the anonymous referee for drawing attention to the extreme abundance discrepancies in the PB4 nebula and also for valuable and constructive comments which have greatly improved the manuscript. MD acknowledges the support of the Australian Research Council (ARC) through Discovery project DP16010363. Parts of this research were conducted by the Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), through project number CE170100013.

REFERENCES

Ali A., Ismail H. A., Alsolami Z., 2015a, ApkSS, 357, 21
Ali A., Amer M. A., Dopita M. A., Vogt F. P. A., Basurah H. M., 2015b, A&A, 583, A83
Ali A., Dopita M. A., Basurah H. M., Amer M. A., Alsulami R., Alruhaili A., 2016, MNRAS, 462, 1393
Basurah H. M., Ali A., Dopita M. A., Alsulami R., Amer M. A., Alruhaili A., 2016, MNRAS, Bohigas J., Rodríguez M., Dufour R. J., 2013, Rev. Mexon. Astron. Astrophys., 49, 227
Bohigas J., Escalante V., Rodríguez M., Dufour R. J., 2015, MNRAS, 447, 817
Cahn J. H., Kaler J. B., Stanghellini L., 1992, A&AS, 94, 399
Childress M. J., Vogt F. P. A., Nielsen J., Sharp R. G., 2014, ApkSS, 349, 617
Corradi R. L. M., Schönberner D., Steffen M., Perinotto M., 2003, MNRAS, 340, 417
Corradi R. L. M., García-Rojas J., Jones D., Rodríguez-Gil P., 2015, ApJ, 803, 99
Cuisiner F., Acker A., Koeppen J., 1996, A&A, 307, 215
Delgado-Ingliada G., Morisset C., Stasińska G., 2014, in Revista Mexicana de Astronomia y Astrofisica Conference Series. pp 17–17
Dopita M. A., Sutherland R. S., 2000, ApJ, 531, 231
Dopita M., Ali A., Karakas A. I., Goldman D., Amer M. A., Sutherland R. S., 2018, MNRAS, 475, 424
Durand S., Acker A., Zijlstra A., 1998, A&AS, 132, 13
Ercolano B., Morisset C., Barlow M. J., Storey P. J., Liu X.-W., 2003, MNRAS, 340, 1153
Faundez-Abans M., Maciel W. J., 1987, A&A, 183, 324
Frew D. J., Bojić I. S., Parker Q. A., 2013, MNRAS, 431, 2
Frew D. J., Parker Q. A., Bojić I. S., 2016, MNRAS, 455, 1459
García-Rojas J., Corradi R. L. M., Monteiro H., Jones D., Rodríguez-Gil P., Cabrera-Lavers A., 2016, ApJ, 824, L27
Gieseking F., Hipsey H., Weinberger R., 1986, A&A, 156, 101
Gleizes F., Acker A., Stenholm B., 1989, A&A, 222, 237
Henry R. B. C., Balick B., Dufour R. J., Kwitter K. B., Shaw R. A., Miller T. R., Buell J. F., Corradi R. L. M., 2015, ApJ, 813, 121
Howarth I. D., 1983, MNRAS, 203, 301
Huyng S., Pottasch S. R., Feibelman W. A., 2004, A&A, 425, 143
Jenkins E. B., 2009, ApJ, 700, 1299
Jones D., Boffin H. M. J., Rodríguez-Gil P., Wesson R., Corradi R. L. M., Miszalski B., Mohamed S., 2015, A&A, 580, A19
Jones D., Wesson R., García-Rojas J., Corradi R. L. M., Boffin H. M. J., 2016, MNRAS, 455, 3263
Kaler J. B., Jacoby G. H., 1989, ApJ, 345, 871
Liu X.-W., Storey P. J., Barlow M. J., Danziger I. J., Cohen M., Bryce M., 2000, MNRAS, 312, 585
Livadiolos G., 2018, epl, 122, 50001
Maciel W. J., Quiroa C., 1999, A&A, 345, 629
Meatheringham S. J., Wood P. R., Faulkner D. J., 1988, ApJ, 334, 862
Milingo J. B., Kwitter K. B., Henry R. B. C., Cohen R. E., 2002a, ApJS, 138, 279
Milingo J. B., Henry R. B. C., Kwitter K. B., 2002b, ApJS, 138, 285
Miller Bertolami M. M., 2016, A&A, 588, A25
Miszalski B., 2009, PhD thesis, Department of Physics, Macquarie University, NSW 2109, Australia
Miszalski B., Corradi R. L. M., Boffin H. M. J., Jones D., Sabin L., Santander-García M., Rodríguez-Gil P., Rubio-Díez M. M., 2011, MNRAS, 413, 1264
Morisset C., Georgiev L., 2009, A&A, 507, 1517
Nicholls D. C., Dopita M. A., Sutherland R. S., 2012, ApJ, 752, 148
Otsuka M., Kemper F., Cami J., Peeters E., Bernard-Salas J., 2014, MNRAS, 437, 2577
Peimbert M., 1978, in Terzian Y., ed., IAU Symposium Vol. 76, Planetary Nebulae. pp 231–240
Peimbert M., Torres-Peimbert S., 1983, in Flower D. R., ed., IAU Symposium Vol. 103, Planetary Nebulae. pp 233–234
Pottasch S. R., Surendiranath R., 2005, A&A, 444, 861
Pottasch S. R., Surendiranath R., Bernard-Salas J., Roellig T. L., 2009, A&A, 506, 189
Pottasch S. R., Surendiranath R., Bernard-Salas J., 2011, A&A, 531, A23
Quiroa C., Rocha-Pinto H. J., Maciel W. J., 2007, A&A, 475, 217
Rauch T., 2003, A&A, 403, 709
Reid W. A., Parker Q. A., 2010, Publ. Astron. Soc. Australia, 27, 187
Rubin R. H., 1986, ApJ, 309, 334
Schwarz H. E., Corradi R. L. M., Melnick J., 1992, A&AS, 96, 23
Sharpee B., Zhang Y., Williams R., Pellegrini E., Cavagnolo K. Baldwin J. A., Phillips M., Liu X.-W., 2007, ApJ, 659, 1265
Soker N., 1997, ApJS, 112, 487
Sowicka P., Jones D., Corradi R. L. M., Wesson R., García-Rojas J., Santander-García M., Boffin H. M. J., Rodríguez-Gil P., 2017, MNRAS, 471, 3529
Sterling N. C., Porter R. L., Dinerstein H. L., 2015, ApJS, 218, 25
Surendiranath R., Pottasch S. R., 2008, A&A, 483, 519
Surendiranath R., Pottasch S. R., García-Lario P., 2004, A&A, 421, 1051
Sutherland R. S., Dopita M. A., 2017, ApJS, 229, 34
Tyenda R., Acker A., Stenholm B., Koeppen J., 1992, A&AS, 95, 337

MNRAS 000, 1–?? (2018)
Tylenda R., Acker A., Stenholm B., 1993, AAS, 102, 595
Vassiliadis E., Wood P. R., 1994, ApJS, 92, 123
Weidmann W. A., Gamen R., 2011, A&A, 526, A6
Weidmann W. A., Méndez R. H., Gamen R., 2015, A&A, 579, A86
Weidmann W. A., Schmidt O., Vena Valdarenas R. R., Ahumada J. A., Volpe M. G., Mudrik A., 2016, A&A, 592, A103
Weidmann W., et al., 2018, ArXiv e-prints,
Wesson R., 2016, MNRAS, 456, 3774
Wesson R., Stock D. J., Scicluna P., 2012, MNRAS, 422, 3516
Wesson R., Jones D., García-Rojas J., Boffin H. M. J., Corradi R. L. M., 2018, MNRAS, 480, 4589
Yuan H.-B., Liu X.-W., Péquignot D., Rubin R. H., Ercolano B., Zhang Y., 2011, MNRAS, 411, 1035