A radial velocity survey for post-common-envelope Wolf-Rayet central stars of planetary nebulae: First results and discovery of the close binary nucleus of NGC 5189

Rajeev Manick, Brent Miszalski and Vanessa McBride

1 South African Astronomical Observatory, PO Box 9, Observatory, 7935, South Africa
2 Astrophysics, Cosmology and Gravity Centre, Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa
3 Institut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200D bus 2401, B-3001 Leuven, Belgium
4 Southern African Large Telescope Foundation, PO Box 9, Observatory, 7935, South Africa

ABSTRACT

The formation of Wolf-Rayet central stars of planetary nebulae ([WR] CSPNe) whose spectroscopic appearance mimics massive WR stars remains poorly understood. Least understood is the nature and frequency of binary companions to [WR] CSPNe that may explain their H-deficiency. We have conducted a systematic radial velocity (RV) study of 6 [WR] CSPNe to search for post-common-envelope (post-CE) [WR] binaries. We used a cross-correlation method to construct the RV time-series as successfully done for massive close binary WR stars. No significant RV variability was detected for the late-[WC] type nuclei of Hen 2-113, Hen 3-1333, PMR 2 and Hen 2-99. Significant, large-amplitude variability was found in the [WC4] nucleus of NGC 5315. In the [WO1] nucleus of NGC 5189 we discovered significant periodic variability that reveals a close binary with \( P_{\text{orb}} = 4.04 \pm 0.1 \) d. We measured a semi-amplitude of \( 62.3 \pm 1.3 \) km s\(^{-1}\) that gives a companion mass of \( m_2 \geq 0.5 \) M\(_\odot\) or \( m_2 = 0.84 \) M\(_\odot\) (assuming \( i = 45^\circ\)). The most plausible companion type is a massive WD as found in Fleming 1. The spectacular nebular morphology of NGC 5189 fits the pattern of recently discovered post-CE PNe extremely well with its dominant low-ionisation structures (e.g. as in NGC 6326) and collimated outflows (e.g. as in Fleming 1). The anomalously long 4.04 d orbital period is either a once-off (e.g. NGC 2346) or it may indicate there is a sizeable population of [WR] binaries with massive WD companions in relatively wide orbits, perhaps influenced by interactions with the strong [WR] wind.

Key words: planetary nebulae: general - stars: Wolf-Rayet - stars: AGB and post-AGB - planetary nebulae: individual: NGC 5189 - binaries: spectroscopic

1 INTRODUCTION

Planetary nebulae (PNe) are circumstellar gas envelopes ejected at the end of the Asymptotic Giant Branch (AGB) phase of low-intermediate mass stars of \( \sim 1 \) M\(_\odot\) to 8 M\(_\odot\). A majority of central stars of planetary nebulae (CSPNe) show hydrogen rich atmospheres (e.g. Méndez et al. 1988; Méndez 1991; Napiwotzki & Schoenberner 1995), with their spectra containing only weak absorption lines, mainly of hydrogen \((\text{H})\) and helium \((\text{He})\). Perhaps the least understood are the less numerous emission-line CSPNe with H-deficient atmospheres whose spectral appearance mimics the massive Wolf-Rayet (WR) stars. These CSPNe exhibit dense and strong stellar winds with mass-loss rates up to \( \sim 10^{-7} \) M\(_\odot\) yr\(^{-1}\) (e.g. Koesterke 2001; Crowther 2008). Their classification is similar to massive WR stars where the dominant emission lines indicate either a [WC] (He, C and O; Crowther et al. 1998) or [WN] (He and N; Smith et al. 1996) subtype, where the brackets around the spectral type distinguish them from their massive counterparts. In contrast to the roughly equal division between WN and WC subtypes in massive WR stars (van der Hucht 2001), the known examples of [WR] stars are heavily skewed towards early and late [WC] types with few
intermediate [WC] types (Crowther 2008; see however Górný 2014), whereas only two bona-fide [WN] CSPNe were established recently in IC 4663 (Miszalski et al. 2012) and A 48 (Todt et al. 2013; Frew et al. 2014). Comprehending this disparity may shed much needed light on how [WR] stars form.

The most peculiar aspect of the newly discovered [WN] CSPNe is that their atmospheres are extremely helium rich (85–95 per cent by mass, Miszalski et al. 2012; Todt et al. 2013). Therefore, they do not fit into the C-rich evolutionary sequence that the vast majority of H-deficient post-AGB stars follow (Werner & Herwig 2006). The C-rich H-deficient post-AGB evolutionary sequence of [WC] stars evolving into PG1159 stars, the latter characterised by significantly weaker winds and higher surface gravities, is well supported by similar atmospheric abundance patterns between the two classes (Crowther 2008; Werner et al. 2008). Werner (2012) suggested that [WN] CSPNe ‘might’ be the progenitors of O(He) stars, namely a rare group of four high surface gravity He-rich post-AGB stars, two of which are surrounded by PN (Rauch et al. 1994, 1996, 1998, 2008; Reindl et al. 2013, 2014). However, the existence of [WN] CSPNe was still unproven at this time and PB 8 was not He-rich enough to be strictly comparable to the O(He) stars.

Only with the discovery of the extremely He-rich atmosphere of the [WN3] CSPN of IC 4663 (95 per cent He by mass) could the O(He) stars, which are similarly He-rich with He mass fractions ≥90 per cent (Reindl et al. 2013, 2014), be securely linked to [WN] CSPNe in a separate He-rich H-deficient post-AGB evolutionary sequence [WN → O(He)] by Miszalski et al. (2012). In this new sequence the O(He) stars are the He-rich analogues of the C-rich PG1159 stars.

A key question prompted by the discovery of the He-rich sequence is whether it operates in a similar fashion to the C-rich sequence. Is the appearance of the [WR] phenomenon produced by the same recipe? Or is the phenomenon produced via separate routes with different recipes? There are compelling arguments to include binary interactions in the formation of some [WC] CSPNe and related objects (De Marco & Soker 2002; De Marco 2008) for which an irradiation effect would not be detected (e.g. Schoenberner 1979; Blöcker 2001; Herwig 2001), a very late evolutionary sequence for which the stan-

1 These scenarios cannot reproduce the moderate level of ~55 per cent He by mass in the possible intermediate [WN/WC] CSPN of PB 8 (Todt et al. 2010). Miller Bertolami et al. (2011) proposed a diffusion induced nova scenario to explain the abundance pattern of PB 8, however these models require low metallicities and core masses to reach the extremely He-rich compositions of [WN] CSPNe (see the discussion in Todt et al. 2013). While it seems that low metallicities may facilitate [WR] formation (Zijlstra et al. 2006; Kniazev et al. 2008), the α-element nebular abundances of both IC4663 and A 48 are notably Solar, suggesting the Miller Bertolami et al. (2011) scenario may not be applicable.

2 See Table A1 in Appendix for an updated compilation.
2 OBSERVATIONS

2.1 Sample selection

Table 1 gives the basic properties of the objects considered in this pilot study. All were monitored using the cassegrain spectrograph (SpCCD) on the South African Astronomical Observatory (SAAO) 1.9-m telescope except for NGC 5189 which was observed with the Robert Stobie Spectrograph (RSS; Burgh et al. 2003; Kobulnicky et al. 2003) on the queue-scheduled Southern African Large Telescope (SALT; Buckley, Swart & Meiring 2006; O'Donoghue et al. 2006). In general we required the spectra to have a resolution of $\lesssim 2\AA$ (full-width at half maximum, FWHM) and $S/N \gtrsim 40$ in the continuum to be able to ensure cross-correlation techniques could achieve a velocity accuracy of $\sim 10$ km s$^{-1}$ or better. Given the relatively poor throughput of SpCCD, we were heavily restricted in our choice of WR CSPNe to monitor, namely those brighter than $V \lesssim 14$ mag. Therefore we selected several suitably bright targets visible at the time of observations from Acker & Neiner (2003) and one from Morgan et al. (2001). The magnitude restrictions also imposed a bias towards intrinsically brighter late [WC] CSPNe. The sample observed by the SAAO 1.9-m is not particularly remarkable, apart from the peculiar morphologies of Hen 2-113 (Lagadec et al. 2006) and Hen 3-1333 (Chesenau et al. 2006). Both Hen 2-113 and Hen 3-1333 exhibit dual-dust chemistry which may have originated from binary evolution. A binary system may be necessary to explain the resolved dust disk in Hen 3-1333 (De Marco et al. 2002; Chesenau et al. 2006) as they are a prevailing feature of post-AGB binaries (Van Winckel et al. 2009). The inclusion of NGC 5189 was specially motivated for SALT observations as described in the following.

NGC 5189 (PN G307.2–03.4) is a bright, remarkably peculiar southern PN that has long perplexed astronomers. It was discovered in 1826 by J. Dunlop from Australia (Cozens, Walsh & Orchiston 2010), but its unusual appearance meant that it was not until much later that it was recognised to be a PN with a ‘quasi-planetary’ classification assigned by Henize (1967). The filamentary nebula has been described as ‘a graceful affair of recurvant gaseous draperies’ (Evans 1968) and its notorious complexity is the result of multiple point-symmetric low-ionisation knots or ansae (Phillips & Reay 1983; Hua, Dopita & Martinis 1998; Gonzãlez et al. 2001; Sabin et al. 2012). Phillips & Reay (1983) suggested that the point-symmetric features were the result of precession due to a binary nucleus with an orbital period on the order of a few days. Unfortunately, since then no efforts have been made in the literature to determine if NGC 5189 has a close binary nucleus. The central star has a [WO1] spectral type (Crowther et al. 1998) and is amongst the hottest of all central stars at 165$^{+8}_{-3}$ kK (Keller et al. 2014). Ciardullo & Bond (1996) monitored the central star for $\sim 9$ hours and found a low-amplitude pulsation period of 11.51 $\pm 0.05$ min that is typical of stars of its ilk (Ciardullo & Bond 1996; Gonzalez-Perez et al. 1996), but noted no other variability that might otherwise indicate a companion is present.

2.2 SAAO 1.9-m spectroscopy

Table 2 gives a summary of the observations with the SpCCD spectrograph on the SAAO 1.9-m. They were conducted over two separate weeks namely May 16 to 23 of 2012 and June 26 to 4 of 2012. We use the modified julian date (MJD=JD-2400000.5) as the time of the middle of each exposure. A slit width of 1.5” was used. Both grating 4 (1200 lines mm$^{-1}$) and 6 (600 lines mm$^{-1}$) were used in the observing runs. A dispersion of 0.49 and 1.09 Â/pix for the high resolution and low resolution spectra were obtained, respectively. The wavelength coverage of grating 4 is 855 Â at $\sim 1.09$ Â resolution (FWHM) and 1840 Â at $\sim 2.4$ Â resolution (FWHM) for grating 6. The CCD was read out with a binning factor of $1\times2$ in dispersion and spatial axes, respectively. A Copper Argon (CuAr) arc lamp was taken before and after each exposure to calibrate the wavelength scale. Both short ($\sim 240$ s) and long exposures ($\sim 2400$ s) were taken for each target, since we needed both unsaturated nebular emission lines and deep enough exposures to reach a $S/N$ of $>30 – 40$ in the continuum. The $S/N$ was measured as an average of 4 different $S/N$ at wavelengths $\sim 4220$ Â, 4755 Â, 5290 Â and 5620 Â for the blue spectra and $\sim 5990$ Â, 6415 Â, 6950 Â and 7370 Â for the red. The mean spectral resolution varied from 2.5 Â to 2.9 Â. The observations were mostly made when the seeing ranged between $\sim 1.5”$ to $2.5”$. The wavelength range was chosen according to the moon phase (blue wavelengths for grey/dark and red wavelengths for bright).

The 2D frames were trimmed and the overscan region bias level was subtracted. The L.A. Cosmic (van Dokkum 2001) IRAF task was used to cosmic-ray-clean the images. Wavelength calibration was performed in the standard fashion and the mean rms achieved in the IRAF task IDENTIFY was $\sim 0.09$ and $\sim 0.15$ for high and low resolution spectra, respectively. Each solution was applied to the appropriate object spectrum by adding the FITS header keywords RESTSPEC1 and RESTSPEC2 in the header of the object and processing them with the IRAF task DISPCOR. The two arcs were interpolated for the final solution, in case there was any small shift in the arc during the exposure (e.g. due to influence of gravity on the grating causing flexure). We did not find evidence of any substantial shift in the arcs. One-
dimensional spectra were extracted using the APALL task. The CSPN was extracted, subtracting the immediate nebular background (4 pixels either side). However, for late [WC] types this becomes difficult due to a lack of clearly-defined nebular emission lines.

2.3 SALT RSS spectroscopy

We obtained 14 RSS spectra of NGC 5189 with the queue-scheduled SALT under programme 2013-2-RSA-005 (PI: Miszalski). Table 2 includes the log of observations taken during January to March 2014. The PG2300 grating was used at a camera articulation angle of 70 deg to cover a spectral range of 3450–9100 Å. The 1.5 arcsec wide slit was used at a position angle of 90 deg and resulted in a mean resolution of 2.1 Å (FWHM) and a mean dispersion of 0.32 Å/pix. The S/N was measured as an average of 4 different S/N at wavelengths ~ 4580 Å, 4770 Å, 5040 Å and 5225 Å for all spectra. A ThAr arc lamp exposure was taken before and after each science exposure. Basic reductions were applied using the PY SALT package (Crawford et al. 2010) and cosmic ray events were cleaned using the LACOSMIC package (van Dokkum 2001). Wavelength calibration was performed using standard IRAF tasks IDENTIFY, REIDENTIFY, FITCOORDS and TRANSFORM by identifying the arc lines in each row and applying a geometric transformation to the data frames. Both the before and after arc exposures were used to derive the fit for the geometric transformation and the resulting wavelength solution for all spectra had an RMS of 0.06 ± 0.02 Å. One-dimensional spectra were extracted using the APALL task, namely a main extraction of the CSPN where the immediate nebular background (10 pixels on either side corresponding to 5.1 arcsec) was subtracted and a second extraction of the nebula were the subtracted background was taken from outside the nebula (15 pixels on one side only corresponding to 7.6 arcsec) to perform measurement of nebular radial velocities close to the CSPN position. No flux calibration was performed as the spectra were normalised for the cross-correlation analysis (see Figure 2).

In Figures 1 and 2 we show representative spectra of each object split over the whole wavelength range. The strongest over-subtracted nebular lines in the spectra of NGC 5189 have been interpolated over.

3 METHOD

3.1 Cross-correlation method & template construction

The method used for finding radial velocity (RV) shifts in the spectra is cross-correlation as described by Foellmi et al. (2003). The cross-correlation task used is XCSAO found in the RVSAO package (Kurtz & Mink 1998) that is executed in the IRAF environment. XCSAO multiplies the Fourier Transform (FT) of the object spectrum with the conjugate of the transform of a high S/N ratio zero-velocity template. For a detailed overview of the cross-correlation analysis, see Tonry & Davis (1979). This method has proved to be very useful in finding RV shifts in close massive WR binaries (Foellmi et al. 2003; Sana et al. 2013; Schnurr 2008; Schnurr et al. 2009). Despite the strong winds in [WR] CSPNe, this method is still applicable for finding binaries in these systems.

For a consistent RV monitoring programme, the cross-correlation template must have high S/N in the continuum. The object spectra need to be cross-correlated with this high SNR zero-velocity template to obtain accurate RV shifts. After having applied a heliocentric correction to the radial velocities using the BCVCORR package in IRAF, the template was constructed. The main steps involved in creating the template is outlined as follows:

(i) Normalise all spectra.
(ii) Subtract unity from the continuum.
(iii) Convert all spectra to a logarithmic wavelength scale.
(iv) Use the spectrum which has the highest S/N in the continuum as first template (T1) for cross-correlation.
(v) Use the output by XCSAO of the first cross-correlation results to shift all spectra to the same “zero-velocity” as the T1 template.
(vi) Finally, combine all the shifted spectra to create a zero-velocity template (T2) using the IRAF task SCOMBINE providing greater weights to the spectra having higher S/N in the continuum.

Once the template T2 was built, the cross-correlation is run again on the spectra, but with T2 as the template. The spectral regions which contain most of the stellar lines (excluding the nebular emission lines as far as possible) were

Table 1. Basic properties of the sample of [WR] CSPNe observed.

| PNG     | Name      | RA      | Dec     | V        | Type    | Epochs | Ref. |
|---------|-----------|---------|---------|----------|---------|--------|------|
| 291.3+08.4 | PMR 2     | 11 34 38.6 | −52 43 33 | 13.3     | [WC9/10] | 7      | c    |
| 307.2−03.4 | NGC 5189  | 13 33 32.8 | −65 58 27 | 14.5     | [WO1]   | 14     | b,d  |
| 309.0−04.2 | Hen 2-99  | 13 52 30.7 | −66 23 26 | 13.3     | [WC9]   | 7      | a,b  |
| 309.1−04.3 | NGC 5315  | 13 53 57.1 | −66 30 51 | 14.4     | [WC4]   | 4      | a,b  |
| 321.0−03.9 | Hen 2-113 | 14 59 53.5 | −54 18 07 | 11.9     | [WC10]  | 12     | a,b  |
| 332.9−09.9 | Hen 3-1333| 17 09 00.9 | −56 54 48 | 10.9     | [WC10]  | 7      | a,b  |

References: (a): Acker and Neiner (2003). (b): Crowther et al. (1998). (c): Morgan et. al. (2001). (d): Ciardullo et al. (1999).
Figure 1. Representative spectra of objects in our sample.
Figure 2. Figure 1 (continued). Note the HeII 4686 nebular residual in NGC 5189 and the chip gaps at λ = 4955 Å to 4961 Å and λ = 5142 Å 5161 Å.
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Table 2. Table showing the log of observations for the sample.

| Object   | MJD (Days) | Date (MM/DD/YYYY) | Exp. time (s) | Grating | λ (Å) | Dispersion (Å pix$^{-1}$) | $\langle$ S/N $\rangle$ | FWHM (Å) |
|----------|-------------|--------------------|---------------|---------|-------|---------------------------|------------------------|-----------|
| Hen 2-113| 56063.812846| 05/16/2012         | 300           | 4       | 4260-5115 | 0.49                  | 25                     | 1.5        |
|          | 56063.823819| 05/16/2012         | 900           | "       | 4257-5115 | 0.49                  | 50                     | 1.1        |
|          | 56063.839880| 05/16/2012         | 900           | "       | 4257-5115 | 0.49                  | 28                     | 1.1        |
|          | 56063.869755| 05/16/2012         | 1200          | "       | 4257-5115 | 0.49                  | 48                     | 1.3        |
|          | 56064.122231| 05/17/2012         | 1500          | "       | 4257-5115 | 0.49                  | 31                     | 1.3        |
|          | 56064.801191| 05/16/2012         | 1500          | "       | 4257-5115 | 0.49                  | 34                     | 1.3        |
|          | 56069.996481| 05/16/2012         | 1500          | "       | 4257-5115 | 0.49                  | 30                     | 1.3        |
|          | 56106.823001| 06/28/2012         | 1500          | "       | 4257-5115 | 0.49                  | 34                     | 2.8        |
|          | 56108.917004| 06/30/2012         | 1500          | "       | 4257-5115 | 0.49                  | 50                     | 2.6        |
|          | 56108.928125| 06/30/2012         | 1500          | "       | 4257-5115 | 0.49                  | 83                     | 2.7        |
|          | 56110.813025| 07/01/2012         | 1800          | "       | 5722-7565 | 1.06                  | 79                     | 2.4        |
|          | 56111.030991| 07/02/2012         | 1500          | "       | 5722-7567 | 1.06                  | 53                     | 2.5        |
| Hen 2-99 | 56068.820887| 05/21/2012         | 1800          | 6       | 4025-5937 | 1.10                  | 43                     | 2.7        |
|          | 56106.744197| 06/28/2012         | 1800          | "       | 4036-5947 | 1.10                  | 45                     | 2.7        |
|          | 56107.745127| 06/29/2012         | 1800          | "       | 4036-5950 | 1.10                  | 25                     | 2.7        |
|          | 56108.866659| 06/30/2012         | 2400          | "       | 5722-7565 | 1.06                  | 29                     | 2.5        |
|          | 56109.747499| 07/01/2012         | 2400          | "       | 5721-7565 | 1.06                  | 23                     | 2.5        |
|          | 56110.976449| 07/02/2012         | 2400          | "       | 5722-7565 | 1.06                  | 38                     | 2.6        |
|          | 56111.821737| 07/03/2012         | 860           | "       | 5721-7565 | 1.06                  | 25                     | 2.7        |
| Hen 3-1333| 56106.927875| 06/28/2012         | 1200          | 6       | 4036-5947 | 1.10                  | 61                     | 2.6        |
|          | 56108.109317| 06/29/2012         | 1800          | "       | 4032-5940 | 1.10                  | 46                     | 2.7        |
|          | 56108.899327| 06/30/2012         | 1800          | "       | 5722-7567 | 1.06                  | 34                     | 2.4        |
|          | 56109.131929| 07/01/2012         | 2400          | "       | 5722-7570 | 1.06                  | 50                     | 2.4        |
|          | 56109.873401| 07/01/2012         | 2400          | "       | 5722-7572 | 1.06                  | 50                     | 2.4        |
|          | 56109.966351| 07/01/2012         | 2400          | "       | 4035-5948 | 1.10                  | 64                     | 2.7        |
|          | 56111.057141| 07/03/2012         | 1500          | "       | 4029-5948 | 1.10                  | 89                     | 2.6        |
| NGC 5315 | 56068.848701| 05/21/2012         | 1500          | 6       | 4025-5939 | 1.10                  | 30                     | 2.7        |
|          | 56106.777051| 06/28/2012         | 1500          | "       | 4036-5947 | 1.10                  | 24                     | 2.7        |
|          | 56109.782759| 07/01/2012         | 2400          | "       | 4033-5944 | 1.10                  | 24                     | 2.7        |
|          | 56110.737799| 07/02/2012         | 2400          | "       | 4014-5929 | 1.10                  | 23                     | 2.7        |
| PMR 2    | 56106.715497| 06/28/2012         | 1800          | "       | 4036-5948 | 1.10                  | 32                     | 2.6        |
|          | 56107.709237| 06/29/2012         | 1800          | "       | 4036-5948 | 1.10                  | 27                     | 2.6        |
|          | 56108.713127| 06/30/2012         | 2400          | "       | 5722-7565 | 1.06                  | 40                     | 2.5        |
|          | 56109.713500| 07/01/2012         | 2400          | "       | 5722-7565 | 1.06                  | 30                     | 2.4        |
|          | 56109.843839| 07/01/2012         | 2400          | "       | 5722-7565 | 1.06                  | 15                     | 2.6        |
|          | 56110.721211| 07/02/2012         | 1800          | 6       | 4036-5948 | 1.10                  | 37                     | 2.7        |
|          | 56110.735899| 07/02/2012         | 2400          | "       | 4015-5927 | 1.10                  | 36                     | 2.7        |
| NGC 5189 | 56672.581101| 01/15/2014         | 900           | "       | PG2300   | 4440-5462 | 0.32                  | 63                     | 2.1        |

used for cross-correlation because nebular lines may dilute any shifts measurable from the stellar lines. Table 3 gives an outline of the wavelength ranges used for cross-correlation. Following the Foellmi et al. (2003) method we used the bisector method to determine the absolute zero-point velocity of T2 to put all the other measurements into heliocentric velocities. Table 4 summarises the strongest stellar emission lines chosen for this purpose together with their mean heliocentric velocity and the mean RV of the nebula measured separately from our observations. The online tool vospec (Osuna et al. 2005) was used for bisecting the chosen emission line in the template spectrum and to obtain the absolute
RV of the template using the central wavelength (observed) and rest wavelength obtained from the NIST website. The fraction of the emission line height (h) used to obtain the middle point varied for different objects. For different lines, an estimate was made to the portion which is more or less halfway between the true peak and the average peak. The mean error in the individual RVs (v) was computed using:

\[ \sigma_i = \sqrt{\sigma^2_{r\text{c}} + \sigma^2_{\text{sector}}} \]

Where \( \sigma^2_{r\text{c}} \) is the error measurement for the bisector method and \( \sigma^2_{\text{sector}} \) is the error output by XCSAO as described by Kurtz & Mink (1998). A peak is selected by fitting a smooth curve with accurate values of \( \delta \) (the central value), \( h \) (the height of the central peak) and \( w \) (the FWHM of the peak). Kurtz & Mink (1998) assumed a sinusoidal noise profile, with the halfwidth of the sinusoid equal to the halfwidth of the correlation peak. The mean error output by XCSAO is a single velocity measurement and is given by:

\[ \text{error} = \frac{3}{8} \frac{w}{(1+r)} \]

Where \( w \) is the FWHM of the correlation peak and \( r \) is defined in Tonry & Davis (1979), as the ratio of the height of the true peak to the average peak.

### 3.2 Construction of RV time-series

The main outputs by XCSAO are the RV shift in km s\(^{-1}\) of the object spectrum relative to the T2 template together with the height of the cross-correlation peak and the associated error in km s\(^{-1}\). In summary, the velocity obtained by the bisector represents the mean stellar velocity and the RVs are computed using:

\[ v_i = v_{\text{r\text{c}}} + v_{\text{sector}} + v_{\text{hcv}} \]

Where \( v_{\text{r\text{c}}} \) is the RV output by XCSAO, \( v_{\text{sector}} \) is the stellar mean RV calculated using the bisector method and \( v_{\text{hcv}} \) is the heliocentric velocity correction.

The error in the individual RVs (\( v_i \)) was computed in quadrature using the equation:

\[ \Delta v_i = \sqrt{\Delta v^2_{r\text{c}} + \Delta v^2_{\text{sector}}} \]

Where \( \Delta v_{r\text{c}} \) is the error measurement for the bisector method and \( \Delta v_{r\text{c}} \) is the error output by XCSAO as described by Kurtz \& Mink (1998). A peak is selected by fitting a smooth curve with accurate values of \( \delta \) (the central value), \( h \) (the height of the central peak) and \( w \) (the FWHM of the peak). Kurtz \& Mink (1998) assumed a sinusoidal noise profile, with the halfwidth of the sinusoid equal to the halfwidth of the correlation peak. The mean error output by XCSAO is a single velocity measurement and is given by:

\[ \text{error} = \frac{3}{8} \frac{w}{(1+r)} \]

Where \( w \) is the FWHM of the correlation peak and \( r \) is defined in Tonry \& Davis (1979), as the ratio of the height of the true peak to the average peak.

**Table 3.** The wavelength ranges chosen for the cross-correlations of stellar lines. The empty fields (−) mean either no observations were made in that particular wavelength range or not enough spectra were available for cross-correlation.

| Object  | Blue wavelength range (Å) | Red wavelength range (Å) |
|---------|---------------------------|--------------------------|
| Hen 2–113 | 4477-4705 & 5050-5500 | 6064-6372 & 6736-7050 |
| Hen 3–1333 | 4500-4720 & 4785-5420 | 6000-6288 & 6734-7057 |
| Hen 2–99 | 4500-5740 | 6630-7300 & 6000-6490 |
| NGC 5315 | 4477-4705 & 5050-5500 | - |
| PMR 2 | 4477-5400 | 6321-6536 & 6838-7055 |
| NGC 5189 | 5200-5450 | - |

### 4 RESULTS

#### 4.1 RV time series

Tables [H1] and [H2] list the resultant RV time-series for each object. Figures [3] and [4] display the data graphically. We emphasise that since the [WR] emission lines are formed in the wind, the absolute values of the velocities may not be meaningful (especially when compared against the nebular RVs). To quantify the variability level observed in each object, we conducted a \( \chi^2 \) analysis of the RV time-series based on a null hypothesis which is discussed in detail by Trumpler \& Weaver (1953). These authors recommend a standard \( \chi^2 \) computation, from the reduced \( \chi^2_{\nu-1} \) (where \( n \) is the number of RV measurements and \( n-1 \) is the number of degrees of freedom) which leads to an estimate of the probability that the star’s RV is variable. In summary, let’s say the hypothesis to be tested is \( H : \text{The semi-amplitude “}A\text{” of a radial velocity variation equals zero.} \), i.e., there is no statistical difference between the observed values (\( x_i \)) and the expected values (\( \bar{x} \)). Then alternatively, the hypothesis is that \( A > 0 \).

The test for \( H \) is such that:

- (i) \( P_1 \) is the probability of rejecting \( H \) when \( H \) is true (i.e., saying \( A > 0 \), when \( A = 0 \)). Now, if we set \( \alpha = 0.05 \) arbitrarily, then in this case, \( P_1 \leq \alpha \).
- (ii) \( P_{II} \) is the probability of accepting \( H \) when \( H \) is false (i.e., saying \( A = 0 \), when \( A > 0 \)). In this case \( P_{II} \) must be a minimum, no matter which orbit. So, maximizing \( \beta \) (where \( \beta = 1 - P_{II} \), is the probability that the test will reject \( H \) when \( H \) is false) in the vicinity of \( A = 0 \).

The compromise consists of allowing the value of \( \beta \) to be at least as large as \( \alpha \). Hence, the criterion for rejection is: reject the hypothesis that \( A = 0 \) whenever:

\[ \sum_{j=1}^{n} \frac{(x_j - \bar{x})^2}{\sigma^2_i} \geq \chi^2_{\alpha,n-1} \]

where

- \( \chi^2_{\alpha,n-1} \) is the standard \( \chi^2 \) value for \( n-1 \) degrees of freedom and probability, \( P = \alpha \).
- \( \bar{x} \) is the stellar mean (Expected value).
- \( x_j \) is the individual values for the stellar RVs.
- \( \sigma_i \) the individual errors in the RVs.

The null hypothesis simply states that there is no statistical difference between the observed value (data) and the expected value which in our case is the stellar mean. The main point is to either accept or reject the null hypothesis with a given probability based on a critical value (\( \alpha = 0.05 \)). If the value of the observed \( \chi^2 \) is less than \( \chi^2_{0.05,n-1} \), we will accept the null hypothesis with a probability of 95%. This means that we are 95% sure that the variations in the RV are random. Contrarily, if the observed \( \chi^2 \) is greater than \( \chi^2_{0.05,n-1} \) then we will reject the null hypothesis with a probability of 95%, meaning the RV is highly variable. The convention we will use here is looking at the probability of accepting the null hypothesis.

The above variability test was run on the 6 objects, assuming the stellar mean is the expected mean and the results are shown in Table [B]. For each of them, the \( \chi^2_{\alpha} \) (observed Chi-squared) was computed and the probability that the object is variable \( P(\chi^2_{\alpha} \geq \chi^2_{\alpha,n-1}) \) was obtained. For some stars,
Table 4. The weighted mean radial velocities for stellar and nebular emission features of each object. The nebular lines used are Hα, Hβ, Hδ, Hγ, NII-6583 and OIII-4959.

| Object     | Stellar | λ<sub>rest</sub> (Å) | ⟨RV<sub>stellar</sub⟩⟩ (km s<sup>−1</sup>) | Nebular | ⟨RV<sub>neb</sub⟩⟩ (km s<sup>−1</sup>) |
|------------|---------|-----------------------|------------------------------------------|---------|------------------------------------------|
| Hen 2-113  | CII     | 4267.26               | −60±4                                    | Hα, Hβ, Hδ, Hγ, NII | −63±2                                    |
| Hen 3-1333 | CIII    | 5695.19               | −43±4                                    | Hα, Hβ, Hγ, NII | −66±10                                    |
| Hen 2-99   | CIII    | 5695.19               | −56±12                                   | Hα, Hβ, NII | −95±13                                    |
| NGC 5315   | HeI     | 4471.47               | 84±15                                    | Hα, Hβ, Hγ, NII, OIII | −24±8                                    |
| PMR 2      | CII     | 4267.18               | 4±5                                      | Hα, Hβ, NII | −66±23                                    |
| NGC 5189   | OVI     | 5290.65               | 23±40                                    | Hβ       | −8±4                                      |

Figure 3. Measured RV time-series for the nuclei of Hen 2-113, Hen 2-99 and Hen 3-1333.
the RV variability was so large that it becomes obvious with only a few observations to decide whether it is a binary or not. However, in most cases we lack sufficient observations to properly constrain the amount of variability in the RV. In cases where small random fluctuations in the RV from the mean occur, which we would expect due to instrumental uncertainties or wind variability, we would identify the RV as being constant. However, a highly variable RV from the mean would be one having large enough RV variations that cannot be assigned solely to random variations. In the case of a close binary CSPN we require a statistically significant periodic signature in the RV time-series to be present.

The objects observed with the SAAO 1.9-m are not sufficiently variable to prove a binary companion is present at this time, however two objects stand out from the rest. Hen 2-99 has stellar RV shifts with a peak-to-peak value of the order 30 km s\(^{-1}\) from the mean and a hint of periodicity is seen with a peak-to-peak of $\sim 53$ km s\(^{-1}\). A sinusoid fits reasonably well with the RV of Hen 2-99 with a period of 5.3 d. More data is needed to confirm this period. Similarly, NGC 5315 shows much higher RV variability ($P_{null} = 1\%$).
but we have only 4 epochs for this object. The non-periodic and relatively small amplitude RV shifts in the remaining objects that we see are most probably due to stochastic wind variability (e.g. Grosdidier et al. 2000, 2001).

NGC 5189 is the only object in the sample that shows very high RV variability with a peak-to-peak velocity of the order of 120 km s\(^{-1}\) (see Fig. 4). From the \(\chi^2\) variability analysis in Table 5 and Fig. 4 it is quite clear that it is the only object which shows 100% variability. The following section further analyses this unique dataset.

### 5 THE CLOSE BINARY CS OF NGC 5189

#### 5.1 Orbital period analysis and mass function

Since our data is not evenly sampled, we used the Lomb-Scargle (Lomb 1976; Scargle 1982) method to search for an orbital period. The Lomb-Scargle method is mainly based on a least-squares fit of sinusoids (Press & Rybicki 1989).

Figure 5 shows four significant peaks in the periodogram at periods 4.04 days, 3.54 days, 1.32 days and 0.80 days. However, we find that the 3.54 day, 1.32 day and 0.80 day peaks are most likely to be aliases, as they do not persist when we ran the Lomb-Scargle for a second time after extracting the 4.04 day period. Moreover, to test the validity of the periods, we further analysed the data according to the method described by Tanner (1948). Assuming the actual period is 4.04 d, both the 1.32 d and the 0.8 d periods satisfy Equation 2 in Tanner (1948). Based on the relatively high value \(\chi^2\) of 8.3 for the 3.54 day period sinusoid fit, we further reject this period. This leaves us with the best period being 4.04 d which has the lowest \(\chi^2\) of 3.0 out of all periods.

A significance test was also carried out on the periods found using a Monte-Carlo simulation, where a random number generator was used to scramble the original radial velocities within one standard deviation, creating 10000 randomised RV curves of the same structure. A Lomb-Scargle analysis was then performed on the randomised RV curves and the highest powers were recorded for each of them. The powers were then sorted in ascending order after which the 90%, 99% and 99.9% significance levels were obtained (displayed as horizontal lines in Fig. 4). The only period which was found to be above the 99.9% level and accepted as per the sinusoid model fit was the 4.04 day.

### Table 5. Results of the variability test carried on individual objects. Column 1 shows the object name, the 2\(^{nd}\) column is the number of RV measurements (degrees of freedom+1), the 3\(^{rd}\) column is the mean RV, the 4\(^{th}\) column is the standard deviation in the RV, the 5\(^{th}\) column is the observed \(\chi^2\) and column 6 shows the probability of accepting the null hypothesis based on the \(\chi^2\) value.

| Object   | \(n\) | \(\langle\text{RV}\rangle\) (km s\(^{-1}\)) | \(\sigma\) (km s\(^{-1}\)) | \(\chi^2\) | \(P_{\text{null}}\) |
|----------|-------|--------------------------------------|-----------------|--------|------------------|
| Hen2-113 | 18    | 59.5                                 | 4.1             | 8.8    | 94%              |
| Hen3-1333| 15    | 44.1                                 | 4.4             | 0.2    | 100%             |
| Hen3-99  | 8     | 55.7                                 | 12.0            | 4.5    | 72%              |
| NGC 5315 | 4     | 87.3                                 | 14.0            | 15.3   | 1%               |
| PMR 2    | 7     | 4.0                                  | 4.8             | 3.9    | 80%              |
| NGC 5189 | 14    | 23.2                                 | 40.1            | 690    | 0%               |

The second panel in Figure 5 is a sinusoidal model determined from fitting the data folded on the 4.04 day period in phase space. We used the MPFIT and MPFITFUN IDL codes designed to perform a Levenberg-Marquardt least-squares fit of a user supplied model to a function (Markwardt 2012). The main fitting was done by MPFIT after specifying a set of initial parameters. Given the data and their uncertainties, MPFITFUN computes the best set of model parameters which match the data and returns them in an array. In time space we determined a 4.04 day period fit of the form

\[
A \sin(2\pi f - \phi) + B
\]

where \(A\) denotes the amplitude, \(f\) is the frequency fixed at 0.247 day\(^{-1}\), \(\phi\) is the phase and \(B\) is the mean, with \(A = 62.3\) km s\(^{-1}\), \(\phi = 0.43\) and \(B = 14.0\) km s\(^{-1}\). This corresponds to an ephemeris determined from the minimum radial velocity at MJD (min RV) = (2456700.24 ± 0.02) + (4.04 ± 0.1)E. The error in the orbital period was determined by fitting a gaussian with a mean of 4.04 d and a standard deviation of 0.1 d to the peak period in the periodogram. The bottom two panels of Fig. 5 shows this fit along with the RV time-series data showing the reasonable agreement to our observations. Figure 5 gives another graphical representation of the periodic motion in the RV time-series data of NGC 5189. The trail diagrams are plotted over 2 phases using the motion of the OVI-5290 stellar emission line and, for comparison, the static H\(\beta\) nebular emission line.

In the case of close-binaries with a good sinusoidal fit, it is fair to assume a low (e<0.1) or zero eccentricity. In this case the mass function of two stars of masses \(m_1\) and \(m_2\), where only one of the stars is visible in the spectrum (single-line spectroscopic binaries) is described by:

\[
f(m_1, m_2) = \frac{m_3^2 \sin^3 i}{(m_1 + m_2)^2} = \frac{P}{2\pi G v_1^3}
\]

where \(P\) is the orbital period (4.04 ± 0.1 d), \(i\) is the inclination of the orbital plane to the line of sight, and \(v_1\) is the semi-amplitude of the RV curve (\(v_1 = 62.3 ± 1.3\) km s\(^{-1}\)).

Table 6 lists companion masses \(m_2\) calculated for a range of inclination values and an adopted \(m_1\) mass of 0.596 \(M_\odot\) for the [WO1] primary. The value of \(m_1\) was calculated as an average of the masses of Miller Bertolami & Althaus (2006) evolutionary tracks either side of the location of NGC 5189 in figure 13 of Keller et al. (2014). There are several caveats associated with this assumption. Firstly, the mass estimates derived from interpolating between evolutionary tracks are distance dependent and distances to PNe are notoriously uncertain. Keller et al. (2014) adopted a distance of 0.55 kpc to NGC 5189 (Stanghellini et al. 2008), but the distance may be as large as 1.44±0.27 kpc based on extinction and kinematic distance estimates (Frew 2008). The luminosity would therefore increase from \(\sim 2.73\ L_\odot\) (Keller et al. 2014) to \(\sim 3.86\ L_\odot\) (Frew 2008), resulting in a mass closer to \(\sim 0.62\ M_\odot\). However, it is not necessarily a matter of adopting this mass as this method of estimating CSPNe masses does not agree well with spectroscopic mass estimates for CSPNe (see section 4.2.3 of Moe & De Marco 2006 and ref. therein), underlying the intrinsic unreliability of such model-dependent methods. Finally, the evolutionary tracks assume single star evolution which may not apply to a post-CE binary such as the nucleus of NGC 5189.

In summary, these caveats make it difficult to choose any ‘best’ value for \(m_1\). As the orbital inclination of the neb.
Figure 5. **Top**: The Lomb-Scargle periodogram showing the significance levels of 90%, 99% and 99.9%. **Middle**: The radial velocity folded on the 4.04 day period fitted with a sinusoidal model. **Bottom**: Plot of the radial velocities folded on the 4.04 day period fitted with a sinusoid.
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Figure 6. Left: Trail diagram of the nebular H\(\beta\) line. Right: Trail diagram of the stellar OVI-5290 emission line. The dashed line shows the sinusoidal fit to the RV curve in phase space.

Table 6. Companion masses \((m_2)\) for NGC 5189 for a variety of orbital inclination angles.

| Inclination | \(m_2\) | \(\Delta m_2\) |
|-------------|---------|---------------|
| \(^{\circ}\) | \((M_\odot)\) | \((M_\odot)\) |
| 30          | 1.56    | 0.03          |
| 35          | 1.21    | 0.02          |
| 40          | 0.99    | 0.02          |
| 45          | 0.84    | 0.01          |
| 50          | 0.74    | 0.01          |
| 55          | 0.67    | 0.01          |
| 60          | 0.61    | 0.01          |
| 65          | 0.57    | 0.01          |
| 70          | 0.54    | 0.01          |
| 75          | 0.52    | 0.01          |
| 80          | 0.51    | 0.01          |
| 85          | 0.50    | 0.01          |
| 90          | 0.50    | 0.01          |

5.2 Nature of the companion

We give a summary of the properties of the CS of NGC 5189 in Table 7 and Table 8 gives the orbital parameters derived in this work. The mass function puts a lower limit on \(m_2\) (0.5 \(M_\odot\) \pm 0.01) which is reached only if the system is edge-on with \(i = 90^\circ\). For inclinations less than 40 degrees we find improbably high values of \(m_2\), suggesting these inclinations can be discarded. At other inclinations the possible companions are a main sequence star or a WD. It may be possible for an orbital period of 4.04 d that a main sequence companion could produce an irradiation effect, especially given the 165 kK temperature of the [WO1] component. This effect could be up to 0.1-0.2 mag (De Marco et al. 2008), but this has not yet been observed (e.g. Ciardullo & Bond 1996). There is also no evidence to suggest a cool companion is present since the intrinsic \((V - I)\) colour of \(-0.32 \pm 0.08\) is typical of hot blue CSPNe \(((V - I)_0 \sim -0.4\), Ciardullo...
and falls into the zone with periods longest currently known amongst post-CE CSPNe (Fig. 7) companion discovered in Fleming 1 (Boffin et al. 2012). It is difficult to decide which of these two possibilities is correct. If the interaction were to facilitate the CE phase at greater orbital separations than in the average post-CE CSPN (WD and main sequence), then the evolution synthesis models (Rebassa-Mansergas et al. 2008; Davis et al. 2010; Nebot Gómez-Morán et al. 2011). There are two possible interpretations for the position of NGC 5189 in the post-CE orbital period distribution. One is that the longer period is a one-off coincidence as in NGC 2346 and this would be in line with the observed deficit. The other possibility is that NGC 5189 reflects the tip of an iceberg where most [WR] close binaries would have similarly long orbital periods (or longer). This could be explained by the stronger and more extended wind of the [WR] component that could interact with the companion (e.g. via wind Roche-lobe overflow, Mohamed & Podsialdowski 2007, 2011). If the interaction were to facilitate the CE phase at greater orbital separations than in the average post-CE CSPN (WD and main sequence), then the resultant orbital period might be longer than the average. At present with only two [WR] post-CE CSPNe known, it is difficult to decide which of these two possibilities is correct.

Table 7. Properties of NGC 5189 and the [WO1] primary.

| Property | Value |
|----------|-------|
| PN G     | 307.2±0.4 |
| $c(H\beta)$ | 0.47±0.08 |
| V (mag)  | 14.53 |
| I (mag)  | 14.35 |
| $(V-I)_0$ | 0.32±0.08 |
| Type     | [WO1] |
| $v_{\infty}$ (km s$^{-1}$) | 250±250 |
| $T_{\text{eff}}$ (kK) | 165$^{+18}_{-8}$ |
| $m_1$ ($M_\odot$) | 0.596 |
| $P_{\text{orb}}$ (d) | 4.04±0.1 |
| e         | 0 (fixed) |
| $K$ (km s$^{-1}$) | 62.3±1.3 |
| $\gamma$ (km s$^{-1}$) | 14±1 |
| $m_2$ ($M_\odot$) | $\geq 0.5$ |
| $T_0$ (MJD) | 56699.74±0.02 |

Table 8. Orbital parameters of NGC 5189.

| Parameter | Value |
|-----------|-------|
| $P_{\text{orb}}$ (d) | 4.04±0.1 |
| e         | 0 (fixed) |
| $K$ (km s$^{-1}$) | 62.3±1.3 |
| $\gamma$ (km s$^{-1}$) | 14±1 |
| $m_2$ ($M_\odot$) | $\geq 0.5$ |
| $T_0$ (MJD) | 56699.74±0.02 |

5.3 The post-CE nebular morphology

The main reason for including NGC 5189 in our study was that it contains all the hallmarks of post-CE nebulae as first outlined by Miszalski et al. (2009b). These hallmarks include low-ionisation structures (LIS; see e.g. Gonçalves et al. 2001), collimated outflows or jets and bipolar nebulae (see also Miszalski et al. 2011b and Miszalski 2012). Additional recent discoveries of post-CE nuclei in other PNe have further reinforced these hallmarks (Corradi et al. 2011; Miszalski et al. 2011a,b,c; Boffin et al. 2012; Jones et al. 2014). The abundance of LIS filaments in NGC 5189 (e.g. Sabin et al. 2012), the majority of which point to the central star, is exactly what we see in NGC 6326 (Miszalski et al. 2011b) and similarly high levels of LIS are also seen in NGC 6778 (Miszalski et al. 2011b; Guerrero & Miranda 2012) and Hen 2-11 (Jones et al. 2014). Secondly, Sabin et al. (2012) demonstrated that the outermost LIS of NGC 5189 have the most extreme velocities of the nebula. Combined with the central S-shaped feature, these outermost LIS are symptomatic of a precessing outflow (e.g. Lopez et al. 1993) that is best explained by jets being launched from a precessing accretion disk around a companion (Cliffe et al. 1995; Raga et al. 2009; Boffin et al. 2012). Furthermore, leaving the LIS aside, the intrinsic morphology of NGC 5189 appears to be a bipolar outflow best seen in the [O III] emission line. It is pinched at the waist at the edges of the minor axis that is closely aligned with slit position 4 in figure 2 of Sabin et al. (2012). As emphasised in Miszalski et al. (2011b) with NGC 6326, there is a stark disconnect between the intrinsic morphology of the nebula and the LIS, the latter of which may form separately to the diffuse components.

6 CONCLUSIONS

We carried out an RV monitoring program of 6 Galactic [WR] CSPNe using a well established cross-correlation method successfully used in massive WR star studies (Oeijlmi et al. 2003). Four of the CSPNe in our sample are late-types ([WCL]) namely Hen 2-99, Hen 2-113, Hen 3-1333 and PMR 2, and two are early-type ([WCE]), namely the
CSPNe of NGC 5189 and NGC 5315. Our main conclusions are as follows:

(i) No significant variability was detected in Hen 2-113, Hen 3-1333 and PMR 2. Hen 2-99 may be variable with a putative periodicity of 5.3 d, but more observations are needed to further investigate. Similarly, NGC 5315 shows a much greater level of variability but will again require more observations to search for an orbital period.

(ii) NGC 5189 showed significant RV variability in stark contrast to the other objects in our sample. A significant period of 4.04 d was found from the Lomb-Scargle periodogram and fitting the phased data gave a peak-to-peak amplitude of $\sim 124$ km s$^{-1}$. The orbital motion is clearly seen in the trailed diagram of the stellar O VI 5290 emission line compared against the static H$eta$ nebular emission line. The mass of the companion $m_2$ has a lower limit of 0.5 M$_\odot$ and may be $\sim 0.9$ M$_\odot$ for a reasonable assumption of the nebular inclination of $i = 45$ degrees. A more massive WD companion is likely to be present, explaining the lack of an irradiation effect in previous photometric observations of the object. Further spatio-kinematic modelling of NGC 5189 as in Sabin et al. (2012) is strongly encouraged to further constrain the inclination and therefore companion mass.

(iii) The spectacular nebula of NGC 5189 further fits the trend for post-CE nebulae to be dominated by low-ionisation structures (e.g. NGC 6326, Miszalski et al. 2011) and to possess precessing outflows (e.g. Fleming 1, Boffin et al. 2012) as first outlined by Miszalski et al. (2009b). Several of the PNe with [WR] nuclei discussed in Miszalski et al. (2009b) are therefore excellent candidates for RV monitoring to discover new [WR] binaries.

(iv) The discovery of a second close binary system containing a [WR] component strongly suggests mergers are not involved in the formation of most [WC] CSPNe. It remains to be seen whether [WN] CSPNe are binary systems. Indeed, the relatively long orbital period of NGC 5189 could be either a one-off coincidence (e.g. NGC 2346) or alternatively it could indicate that potentially many more [WR] binaries may be found if appropriate RV monitoring surveys are conducted. We speculate that wind interactions between the [WR] component and its companion (e.g. wind Roche-lobe overflow) may be responsible for the longer period. Further RV monitoring of [WR] CSPNe is urged to try and discover more systems to place constraints on the formation of [WR] CSPNe.

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APPENDIX A: LIST OF CLOSE-BINARIES

Table A1 gives a list of published post-CE PNe updating Miszalski et al. (2011c). In the Miszalski et al. (2009a) sample, there are still some objects that require spectroscopic confirmation that the variable star identified is the CSPN. Miszalski (2009) obtained Gemini GMOS spectroscopy for several in the sample. Some objects were removed based partially on the spectra (Miszalski et al. 2011c) and several other objects were confirmed by Miszalski (2009) as true central stars (K 6-34, H 2-29, BMP 1800-3408, PPA 1759-2834, Pe 1-9, PPA 1747-3435, PHR 1757-2824, PHR 1756-3342, Sab 41, M 2-19 and M 3-16). Unpublished spectra of other objects have also been obtained, but these will be discussed elsewhere. We have removed Te 11 which is a cataclysmic variable (Drake et al. 2014) and MPA 1508-6455 which requires further work to prove its long 12.5 d period. A period of 1.26 d is adopted for PN G222.8−04.2 based on unpublished SALT RSS radial velocities from our 2013-2-RSA-005 programme.
Table A1. An updated list of 42 close binary CSPNe whose status is fairly well established.

| PN G    | Name     | Period (days) | Discovery reference               |
|---------|----------|---------------|-----------------------------------|
| 053.8−03.0 | Abell 63 | 0.46          | Bond et al. 1978                  |
| 215.6+03.6 | NGC 2346 | 15.99         | Mendez & Niemela 1981             |
| 009.6+10.5 | Abell 41 | 0.23          | Grauer & Bond 1983                |
| 055.4+16.0 | Abell 46 | 0.47          | Bond 1985                          |
| 283.9+09.7 | DS 1    | 0.36          | Drilling 1985                     |
| 136.3+05.5 | HFG 1   | 0.58          | Grauer et al. 1987                |
| 253.5+10.7 | K 1-2   | 0.68          | Bond & Grauer 1987                |
| 005.1−08.9 | Hf 2-2  | 0.40          | Lutz et al. 2010                  |
| 017.3−21.9 | Abell 65 | 1.00          | Bond & Livio 1990                 |
| 329.0+01.9 | Sp 1    | 2.91          | Bond & Livio 1990                 |
| 355.2−03.6 | HaTr 4  | 1.74          | Bond & Livio 1990                 |
| 144.8+65.8 | BE UMa  | 2.29          | Liebert et al. 1995               |
| 135.9+55.9 | SBS 1150+599A | 0.16         | Tovmassian et al. 2004          |
| 341.6+13.7 | NGC 6026 | 0.53          | Hillwig et al. 2010               |
| 349.3−01.1 | NGC 6337 | 0.17          | Hillwig et al. 2010               |
| 359.1−02.3 | M 3-16  | 0.57          | Miszalski et al. 2008             |
| 357.6−03.3 | H 2-29  | 0.24          | Miszalski et al. 2008             |
| 000.2−01.9 | M 2-19  | 0.67          | Miszalski et al. 2008             |
| 005.0+03.0 | Pe 1-9  | 0.14          | Miszalski et al. 2009a            |
| 355.3−03.2 | PPA 1747-3435 | 0.22         | Miszalski et al. 2009a           |
| 357.7−03.0 | H 1-33  | 1.13          | Miszalski et al. 2009a            |
| 354.5−03.9 | Sab 41  | 0.30          | Miszalski et al. 2009a            |
| 000.6−01.3 | Bl 3-15 | 0.27          | Miszalski et al. 2009a            |
| 359.5−01.2 | JaSt 66 | 0.27          | Miszalski et al. 2009a            |
| 358.7−03.0 | K 6-34  | 0.20          | Miszalski et al. 2009a            |
| 357.0−04.4 | PHR 1756-3342 | 0.26      | Miszalski et al. 2009a           |
| 001.8−02.0 | PHR 1757-2724 | 0.80        | Miszalski et al. 2009a           |
| 001.2−02.6 | PHR 1759-2915 | 1.10        | Miszalski et al. 2009a           |
| 005.0−03.1a | MPA 1759-3007 | 0.50       | Miszalski et al. 2009a           |
| 001.9−02.5 | PPA 1759-2834 | 0.31        | Miszalski et al. 2009a           |
| 357.1−05.3 | BMP 1800-3408 | 0.14       | Miszalski et al. 2009a           |
| 000.9−03.3 | PHR 1801-2947 | 0.32       | Miszalski et al. 2009a           |
| 222.8−04.2 | PHR 0654-1045 | 1.26     | Hajduk et al. 2010               |
| 054.2−03.4 | The Necklace | 1.16      | Corradi et al. 2011              |
| 068.1+11.0 | ETHOS 1  | 0.53          | Miszalski et al. 2011a            |
| 049.4+02.4 | Hen 2-428 | 0.18         | Santander-García et al. 2015      |
| 034.5−06.7 | NGC 6678 | 0.15          | Miszalski et al. 2011b            |
| 338.1−08.3 | NGC 6326 | 0.37          | Miszalski et al. 2011b            |
| 290.5+07.9 | Fleming 1 | 1.19          | Boffin et al. 2012               |
| 259.1+00.9 | Hen 2-11 | 0.61          | Jones et al. 2014                |
| 086.9−03.4 | Ou 5    | 0.36          | Corradi et al. 2014              |
| 307.2−03.4 | NGC 5189 | 4.04          | This work                         |
APPENDIX B: LOG OF
CROSS-CORRELATION RESULTS
### Table B1. Log of cross-correlation wavelength ranges, RV shifts, errors and xcsao cross-correlation peak heights $h$.

| Object     | $\lambda$ range (Å) | Grating | MJD (mid)         | $v_i$ (km s$^{-1}$) | $\Delta v_i$ (km s$^{-1}$) | $h$ |
|------------|----------------------|---------|-------------------|---------------------|-----------------------------|-----|
| Hen2-113   | 4477–4705            | 4       | 56063.812846      | –59.7               | 4.9                         | 0.97|
|            |                      |         | 56063.823819      | –60.0               | 4.8                         | 0.97|
|            |                      |         | 56063.836879      | –60.1               | 4.7                         | 0.97|
|            |                      |         | 56063.869755      | –60.3               | 4.5                         | 0.98|
|            |                      |         | 56064.122231      | –56.0               | 4.0                         | 0.97|
|            |                      |         | 56064.801191      | –59.0               | 5.0                         | 0.97|
|            | 5050–5500            |         | 56063.812846      | –61.4               | 7.0                         | 0.81|
|            |                      |         | 56063.823819      | –60.0               | 6.0                         | 0.82|
|            |                      |         | 56063.836879      | –63.0               | 6.0                         | 0.89|
|            |                      |         | 56063.869755      | –60.0               | 6.0                         | 0.92|
|            |                      |         | 56064.122231      | –61.1               | 7.2                         | 0.90|
|            |                      |         | 56064.801191      | –52.9               | 7.0                         | 0.74|
|            | 5050–5500            | 6       | 56069.996481      | –50.5               | 5.0                         | 0.97|
|            |                      |         | 56106.823001      | –60.1               | 4.9                         | 0.98|
|            |                      |         | 56108.917004      | –64.9               | 6.6                         | 0.92|
|            |                      |         | 56108.928125      | –58.2               | 5.6                         | 0.91|
|            |                      |         | 56109.813025      | –68.5               | 5.7                         | 0.89|
|            |                      |         | 56111.030991      | –56.2               | 4.9                         | 0.98|
|            | 4785–5420            |         | 56106.927875      | –41.8               | 4.4                         | 0.98|
|            |                      |         | 56108.109317      | –40.2               | 4.4                         | 0.98|
|            |                      |         | 56109.996351      | –48.2               | 4.7                         | 0.98|
|            |                      |         | 56111.057141      | –47.3               | 4.3                         | 0.99|
| Hen3-1333  | 4500–4720            | 6       | 56106.927875      | –44.8               | 4.1                         | 0.98|
|            | 4785–5420            |         | 56108.098274      | –47.4               | 13.0                        | 0.58|
|            |                      |         | 56108.109317      | –35.0               | 4.3                         | 0.98|
|            |                      |         | 56109.996351      | –47.1               | 4.1                         | 0.98|
|            |                      |         | 56111.057141      | –49.1               | 4.6                         | 0.97|
|            | 6000–6288            |         | 56108.899327      | –45.0               | 4.0                         | 0.98|
|            |                      |         | 56109.131929      | –35.0               | 5.3                         | 0.98|
|            |                      |         | 56109.873401      | –45.1               | 3.9                         | 0.98|
|            | 6734–7057            |         | 56108.899327      | –40.5               | 3.9                         | 0.98|
|            |                      |         | 56109.131929      | –41.2               | 4.3                         | 0.98|
|            |                      |         | 56109.873401      | –45.1               | 3.9                         | 0.98|
| Hen2-99    | 4500–5740            | 6       | 56107.745127      | –35.6               | 13.7                        | 0.98|
|            |                      |         | 56068.820887      | –59.0               | 12.7                        | 0.98|
|            |                      |         | 56110.976449      | –56.0               | 14.3                        | 0.98|
|            |                      |         | 56111.821737      | –54.5               | 12.6                        | 0.98|
|            |                      |         | 56106.744197      | –44.5               | 15.0                        | 0.97|
|            | 6630–7300            |         | 56108.866659      | –62.0               | 14.1                        | 0.96|
|            |                      |         | 56109.747499      | –75.5               | 16.2                        | 0.96|
|            | 6000–6490            |         | 56108.866659      | –58.6               | 15.0                        | 0.87|
| Object | λ range (Å) | Grating | MJD (mid) (Days) | $v_i$ (km s$^{-1}$) | $\Delta v_i$ (km s$^{-1}$) | $h$ |
|--------|-------------|---------|------------------|---------------------|---------------------|------|
| NGC 5315 | 4477–4705 | 6 | 56068.848701 | 93.9 | 6.5 | 0.76 |
| | | | 56106.777051 | 95.8 | 11.5 | 0.83 |
| | | | 56110.773799 | 65.8 | 6.1 | 0.82 |
| | 5050–5500 | 56109.782759 | 79.7 | 6.4 | 0.96 |
| PMR 2 | 4477–5400 | 6 | 56107.709237 | 2.1 | 6.4 | 0.98 |
| | | | 56110.721211 | 4.6 | 12.0 | 0.80 |
| | | | 56110.735899 | −1.3 | 6.2 | 0.98 |
| | | | 56106.715497 | 0.4 | 6.1 | 0.98 |
| | 6321–6536 | 56108.713129 | 9.5 | 6.4 | 0.96 |
| | | | 56109.713509 | 9.7 | 8.5 | 0.94 |
| | | | 56109.843839 | 10.0 | 8.4 | 0.84 |
| NGC 5189 | 5169–5443 | PG 2300 | 56672.581101 | −34.6 | 6.0 | 0.90 |
| | | | 56674.596367 | 36.1 | 7.9 | 0.85 |
| | | | 56677.556460 | 56.7 | 6.0 | 0.86 |
| | | | 56685.583323 | 61.6 | 5.9 | 0.85 |
| | | | 56698.625846 | 70.3 | 5.5 | 0.85 |
| | | | 56700.611668 | −40.4 | 5.6 | 0.87 |
| | | | 56701.611668 | 51.6 | 4.4 | 0.90 |
| | | | 56704.578300 | −37.0 | 6.8 | 0.88 |
| | | | 56705.486876 | 49.4 | 3.7 | 0.88 |
| | | | 56705.506708 | 44.1 | 6.1 | 0.83 |
| | | | 56706.566535 | 57.6 | 5.1 | 0.87 |
| | | | 56707.556766 | −14.9 | 4.9 | 0.91 |
| | | | 56731.589104 | 20.8 | 4.7 | 0.85 |
| | | | 56733.414920 | 4.2 | 3.7 | 0.90 |