

# Newly discovered Wolf–Rayet and weak emission-line central stars of planetary nebulae

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## ABSTRACT

We present the spectra of 32 previously unpublished confirmed and candidate Wolf–Rayet ([WR]) and weak emission-line (WELS) central stars of planetary nebulae (CSPNe). 18 stars have been discovered in the Macquarie/AAO/Strasbourg H $\alpha$  (MASH) PN survey sample, and we have also uncovered 14 confirmed and candidate [WR]s and WELS among the CSPNe of previously known PNe. Spectral classifications have been undertaken using both Acker & Neiner and Crowther, De Marco & Barlow schemes. 22 members in this sample are identified as probable [WR]s; the remaining 10 appear to be WELS. Observations undertaken as part of the MASH spectroscopic survey have now increased the number of known [WR]s by  $\sim 30$  per cent. This will permit a better analysis of [WR] subclass distribution, metallicity effects and evolutionary sequences in these uncommon objects.

**Key words:** stars: Wolf–Rayet – planetary nebulae: general.

## 1 INTRODUCTION

Planetary nebulae (PNe) constitute a short-lived ( $< 10^5$  yr) phase in the life of intermediate-mass ( $\sim 1\text{--}8 M_{\odot}$ ) stars (Iben 1995). The majority of central stars of PNe (CSPNe) have hydrogen-rich atmospheres (Todt, Gräfener & Hamann 2006). There does exist, however, another class of central stars that have H-deficient atmospheres. Some H-deficient CSPNe have strong emission lines of highly ionized carbon, oxygen and helium, and exhibit fast stellar winds and high mass-loss rates (up to  $10^{-6} M_{\odot} \text{ yr}^{-1}$ ) compared to other CSPNe. These stars are known as Wolf–Rayet (denoted by [WR]; van der Hucht et al. 1981) central stars (see Crowther 2008 for a summary of historical classification systems). The quantitative classification schemes currently in use for [WR] subtypes are given by Crowther, De Marco & Barlow (1998) and Acker & Neiner (2003).

[WR] stars are often erroneously referred to as ‘Population II’ WRs to differentiate them from their massive ‘Population I’ counterparts. (While most [WR]s are Population II objects, some are found within Type I PNe, which would indicate the CS to be Population I.) Wind terminal velocities of up to  $3000 \text{ km s}^{-1}$  have been measured in some cases, although late-type [WR]s have much smaller values, sometimes as low as  $\sim 200 \text{ km s}^{-1}$  in [WC10]s and [WC11]s

(e.g. Leuenhagen, Hamann & Jeffery 1996; De Marco & Crowther 1999). There also exists a class of weak emission-line central stars (WELS; see Section 3), which exhibit emission lines at the same wavelengths as those of the Wolf–Rayet types, but with weaker intensities. Unlike [WR]s, WELS do not necessarily have H-deficient atmospheres, though many do (Hajduk, Zijlstra & Gesicki 2010). Because of their similar spectra, our search for Wolf–Rayet type central stars in the MASH data base has resulted in the concomitant discovery of a number of WELS, which are detailed along with the new Wolf–Rayet CSPNe.

While there are nearly 3000 true, likely and possible Galactic PNe currently known (e.g. Frew & Parker 2010a; Jacoby et al. 2010), relatively few central stars have been spectroscopically classified. For example, in the Strasbourg–ESO Catalogue of Galactic Planetary Nebulae (Acker et al. 1992), out of 1143 PNe, only 224 central stars ( $\sim 20$  per cent) were assigned spectral types. More recently, Weidmann & Gamen (2011) have tabulated central star spectroscopic information for only 13 per cent of the enlarged Galactic PN sample. [WR] CSPNe are thought to represent between 5 and 7 per cent of all central stars (Tylenda, Acker & Stenholm 1993; Tylenda 1996; Acker & Neiner 2003; Frew & Parker 2010b), but this may be a lower limit, based on a range of selection effects. For example, when long-slit spectra are obtained for an object, the slit is often positioned over the brightest portion of the PN, missing the central star entirely. For these reasons previously compiled samples may suffer from selection biases and the exact frequency of Wolf–Rayet

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type central stars could be higher than what has been suggested in the recent literature. On the other hand, Górný et al. (2009) find that [WR] PNe are probably the brightest PNe in H $\beta$  in a given sample, so in those samples where the faintest PNe are excluded, there exists the possibility of an overestimation of the frequency of [WR] stars. Interestingly, the fraction of non-DA (hydrogen-deficient) white dwarfs in a local sample is approximately 40 per cent (Sion et al. 2009). This would suggest that the observed proportion of H-deficient central stars, including [WR]s and their progeny (e.g. PG 1159 stars; Werner & Herwig 2006), the presumed progenitors of these non-DA white dwarfs, was previously underestimated.

Observing CSPNe can be difficult. Many are faint in the optical, as distance and interstellar reddening render their observation problematic. Because the classification of [WR]s depends on the measurement of sometimes faint optical lines, reddening will often hide the evidence of emission-line central stars unless deep, high S/N spectra are obtained.

[WR] central stars are thought to result from a final late or very late helium shell thermal pulse after the star has left the AGB phase, which leads to the ingestion or ejection of the remaining thin hydrogen envelope (Herwig 2001; Werner & Herwig 2006). This is effectively the same scenario used in the explanation of H-deficient ejecta inside otherwise normal PNe (e.g. A30 and A78; Jacoby & Ford 1983), also called the ‘born-again’ scenario (Iben et al. 1983). Arguments against the ‘born-again’ scenario can be found in Górný & Tylenda (2000), where the authors find a disparity between model surface brightness predictions and observed values. The ‘born-again’ scenario has also been questioned because the abundances of ‘born-again’ ejecta in A30 and A58 have been found to be oxygen-rich instead of carbon-rich, with an overwhelming amount of neon, more akin to the abundances of neon in nova ejecta (Wesson, Liu & Barlow 2003; Wesson et al. 2008; Lau, De Marco & Liu 2011). Alternative theories have been proposed for the evolutionary sequence of [WR] stars, among them a binary interaction (De Marco & Soker 2002; Gesicki et al. 2006; De Marco 2008). Hajduk et al. (2010) recently found the first close binary [WR] CSPN and suggested that the close binary fraction in the [WR] class may be much lower than for their H-rich counterparts (Miszalski et al. 2009a).

Our incomplete understanding of [WR] evolution is due in part to the dearth of objects in this class which may be examined. Hence, any new additions to the list of known [WR]s are important in constructing a rigorous sample for statistical analysis. Górný et al. (2001) and Acker & Neiner (2003) show that very early type ([WO1]–[WO4]) and late type ([WC8]–[WC11]) stars dominate [WR] CSPNe in the Galaxy, in contrast to the Magellanic Clouds, which seem to possess primarily intermediate types between [WC4] and [WC8] (Peña, Ruiz & Torres-Peimbert 1997). Recent work has revealed that the Galactic bulge [WR]s seem to be heavily weighted towards late spectral subtypes (Górný et al. 2004). In this respect, the bulge [WR] subtype distribution is similar to massive WC stars, which seem to increase in number as the subtype number increases (Crowther 2007).

With a larger sample, it will be possible to put more precise limits on the frequency of [WR]s exhibiting specific subclasses and explore the differences in type distribution between environments of differing metallicity and age. In addition, a greater variation of parameters such as metallicity, temperature, terminal velocity and chemical abundances can be useful in theoretical work which attempts to place constraints on the conditions necessary for H-deficient stellar evolution. In the future, separate samples for the Galactic disc (intermediate age, metal rich) and bulge (old, metal

rich), as well as the Magellanic Clouds (intermediate age, metal poor) may enable us to more precisely lay out the age and metallicity constraints required for the specific subclasses to be produced.

### 1.1 [WR]s in the MASH sample

The number of known Galactic [WR] CSPNe has steadily increased from the late 1960s, when such nuclei were first discovered and classified (Smith & Aller 1969). By the mid-1990s, the count had reached 56 (Jeffery et al. 1996). Discoveries over the past ten years, including our work, have nearly doubled this number to approximately 105. Acker & Neiner (2003) summarized the state of the field early in the decade, listing 86 objects designated to be a [WR] or a [WR] candidate.

The Macquarie/AAO/Strasbourg H $\alpha$  (MASH) surveys of PNe (Parker et al. 2006; Miszalski et al. 2008a) presented  $\sim 900$  and  $\sim 300$  new PNe, respectively.<sup>1</sup> In all, the MASH survey increased the number of known Galactic PNe by nearly 80 per cent. Out of the MASH catalogues, 24 [WR] stars or [WR] candidates have been identified. Only seven of these [WR]s have been previously published in detail, in three previous papers. Morgan, Parker & Russeil (2001, Paper I), detailed the first two discoveries, while another four [WR] central stars were presented by Parker & Morgan (2003, Paper II). A paper on the purported [WN] PM 5 (see Section 3) quickly followed (Morgan, Parker & Cohen 2003, Paper III). This paper represents the fourth in our series concerning new [WR] discoveries, where we describe our additional discoveries in detail and present their spectra. Many of them were listed in brief notes in the online MASH catalogues<sup>2</sup> accompanying Parker et al. (2006) and Miszalski et al. (2008a). Note that the preliminary discovery spectrum for MPA 1611–4356 was shown by Miszalski et al. (2008a) with others noted in the catalogue and referred to generally (but not explicitly) in Miszalski, Acker & Parker (2008b). Four of the objects noted here have been independently identified as [WR]s by Suárez et al. (2006) and Górný et al. (2009), but our observations and identification predate these publications. We note the respective references in the specific subsections devoted to each object.

## 2 SPECTROSCOPIC OBSERVATIONS

Spectroscopic observations of most objects were carried out at the Siding Spring Observatory on the Anglo-Australian Telescope, the 2.3-m telescope, and the UK Schmidt telescope (UKST). Other data were taken at the South African Astronomical Observatory (SAAO) using the 1.9-m telescope and at the European Southern Observatory’s Very Large Telescope during the ESO visitor-mode programme 0.79.D-0764(A). All spectra were bias and flat-field subtracted and dereddened, and in some cases strong nebular lines from the surrounding PN were also subtracted. Those objects with signal-to-noise ratios of 10 or greater were rectified. The instrument and observation details concerning the discovery spectra are listed in Table 1. For long-slit observations, the slit width was set at 2 arcsec. Fibres on AAT 2dF observations are 2.1-arcsec wide. Observations on 6dF on the UKST used 6.7 arcsec fibres.

As discussed in Section 1.1, the majority of the [WR] central stars presented here were identified in the course of spectroscopically confirming MASH PN candidates when the fibre or slit fell across

<sup>1</sup> Note that the MASH-II sample has recently increased to  $\sim 350$  PNe with spectroscopic confirmation pending.

<sup>2</sup> See <http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=V/127>

**Table 1.** Observational details of the new CSPNe discovery spectra.

| PN G       | RA         | Dec.      | Name          | Observatory <sup>a</sup> /<br>telescope | Instrument | Exposure<br>time (s) | Grating     | R           | Signal-to-noise ratio <sup>b</sup> | Date observed    |
|------------|------------|-----------|---------------|-----------------------------------------|------------|----------------------|-------------|-------------|------------------------------------|------------------|
| 001.2–05.6 | 18:11:02.7 | –30:42:11 | PHR 1811–3042 | SSO/AAT                                 | AAΩ-SPIRAL | 1200                 | 385R/580V   | 1300        | 5                                  | 2006 June 28     |
| 016.8–01.7 | 18:27:50.8 | –15:04:23 | BMP 1827–1504 | ESO/VLT-U2                              | FLAMES     | 2400                 | LR2-3/LR5-7 | 8900–12 000 | –                                  | 2007 June 13     |
| 037.7–06.0 | 19:21:44.5 | +01:32:41 | MPA 1921+0132 | SSO/2.3 m                               | DBS        | 300                  | 300B/1200R  | 1200/7000   | –                                  | 2007 May 13      |
| 216.0+07.4 | 07:23:48.4 | +00:36:32 | PHR 0723+0036 | SSO/2.3 m                               | DBS        | 1200                 | 300B        | 1200        | 20                                 | 2007 November 15 |
| 222.8–04.2 | 06:54:13.4 | –10:45:38 | PHR 0654–1045 | SAAO/1.9 m                              | CCD SPEC   | 600                  | 300B (G7)   | 900         | 15                                 | 2003 January 28  |
| 284.2–05.3 | 10:01:18.8 | –61:52:04 | PHR 1001–6152 | SAAO/1.9 m                              | CCD SPEC   | 1200                 | 300B (G7)   | 900         | 20                                 | 2003 February 01 |
| 297.0+06.5 | 12:09:29.1 | –55:53:33 | BMP 1209–5553 | SSO/2.3 m                               | DBS        | 900                  | 300B        | 1200        | –                                  | 2007 February 18 |
| 302.0–01.6 | 12:43:19.4 | –64:28:01 | MPA 1243–6428 | SSO/2.3 m                               | DBS        | 600                  | 300B        | 1200        | –                                  | 2007 February 19 |
| 309.8–01.6 | 13:54:22.4 | –63:37:18 | MPA 1354–6337 | SSO/2.3 m                               | DBS        | 600                  | 300B        | 1200        | –                                  | 2007 February 22 |
| 313.4+06.2 | 14:05:32.2 | –55:07:44 | MPA 1405–5507 | SSO/2.3 m                               | DBS        | 600                  | 300B        | 1200        | 15                                 | 2007 February 22 |
| 313.9+02.8 | 14:16:37.7 | –58:09:32 | PHR 1416–5809 | SAAO/1.9 m                              | CCD SPEC   | 1200                 | 300B (G7)   | 900         | 5                                  | 2002 July 22     |
| 331.8–02.3 | 16:24:02.9 | –52:50:05 | MPA 1624–5250 | SSO/2.3 m                               | DBS        | 3600                 | 300B        | 1200        | 5                                  | 2007 May 13      |
| 336.5+05.5 | 16:11:12.9 | –43:56:22 | MPA 1611–4356 | SSO/2.3 m                               | DBS        | 1200                 | 300B        | 1200        | 5                                  | 2007 February 23 |
| 348.4+04.9 | 16:55:22.0 | –35:35:24 | MPA 1655–3535 | SSO/2.3 m                               | DBS        | 300                  | 300B        | 1200        | 5                                  | 2007 February 28 |
| 355.9–04.4 | 17:53:39.8 | –34:43:40 | PHR 1753–3443 | SSO/UK Schmidt                          | 6dF        | 3 × 600              | 425R        | 1000        | 10                                 | 2003 August 21   |
| 356.0–04.2 | 17:53:04.9 | –34:28:39 | PHR 1753–3428 | SSO/UK Schmidt                          | 6dF        | 3 × 600              | 425R        | 1000        | 5                                  | 2003 August 21   |
| 356.8–03.6 | 17:52:29.2 | –33:30:04 | PHR 1752–3330 | SSO/AAT                                 | AAΩ-2dF    | 1800                 | 385R/580V   | 1300        | 20                                 | 2008 August 8    |
| 359.8+03.5 | 17:31:47.6 | –27:09:18 | PHR 1731–2709 | SSO/AAT                                 | AAΩ-2dF    | 1800                 | 385R/580V   | 1300        | –                                  | 2008 May 30      |
| 000.7–02.7 | 17:58:09.6 | –29:44:20 | M2–21         | SSO/AAT                                 | AAΩ-2dF    | 1800                 | 385R/580V   | 1300        | –                                  | 2008 May 30      |
| 003.9–02.3 | 18:03:39.3 | –26:43:34 | M1–35         | SSO/AAT                                 | AAΩ-2dF    | 1800                 | 384R/580V   | 1300        | 10                                 | 2008 May 29      |
| 008.1–04.7 | 18:22:01.1 | –24:10:40 | M2–39         | SSO/UK Schmidt                          | 6dF        | 1200                 | 385R/580V   | 1000        | 25                                 | 2004 August 11   |
| 008.2–04.8 | 18:22:32.0 | –24:09:28 | M2–42         | SSO/UK Schmidt                          | 6dF        | 1200                 | 385R/580V   | 1000        | 10                                 | 2004 August 20   |
| 029.0+00.4 | 18:42:46.9 | –03:13:17 | Abell 48      | SSO/2.3 m                               | DBS        | 300                  | 1200B/1200R | 5000/7000   | –                                  | 2008 May 11      |
| 270.1–02.9 | 08:59:02.9 | –50:23:40 | Wr 17–23      | SSO/2.3 m                               | DBS        | 1200                 | 300B        | 1200        | 5                                  | 2007 November 17 |
| 322.4–00.1 | 15:23:42.9 | –57:09:25 | Pe 2–8        | ESO/VLT-U2                              | FLAMES     | 1800                 | LR3/LR5-7   | 8900–12 000 | 5                                  | 2007 June 11     |
| 355.4–04.0 | 17:51:12.1 | –34:55:22 | Pe 1–10       | SSO/AAT                                 | AAΩ-2dF    | 1200                 | 385R        | 1300        | 5                                  | 2007 March 27    |
| 356.1+02.7 | 17:25:19.4 | –30:40:42 | Th 3–13       | SSO/AAT                                 | AAΩ-2dF    | 1800                 | 385R        | 1300        | –                                  | 2008 May 30      |
| 356.9+04.4 | 17:21:04.4 | –29:02:59 | M3–38         | ESO/VLT-U2                              | FLAMES     | 1200                 | LR2-3/LR5-7 | 8900–12 000 | –                                  | 2007 June 10     |
| 357.4–03.2 | 17:52:34.4 | –32:45:52 | M2–16         | SSO/AAT                                 | AAΩ-2dF    | 2 × (1800/1500)      | 385R/580V   | 1300        | 5                                  | 2008 August 08   |
| 358.0–04.6 | 17:59:55.0 | –32:59:12 | Sa 3–107      | SSO/AAT                                 | AAΩ-2dF    | 1800                 | 385R/580V   | 1300        | 10                                 | 2008 August 08   |
| 358.9+03.3 | 17:30:02.5 | –27:59:18 | H1–19         | SSO/AAT                                 | AAΩ-2dF    | 1800                 | 385R/580V   | 1300        | 5                                  | 2008 May 30      |
| 359.9–04.5 | 18:03:52.6 | –31:17:46 | M2–27         | SSO/AAT                                 | AAΩ-2dF    | 1800                 | 385R/580V   | 1300        | 5                                  | 2008 May 30      |

<sup>a</sup>ESO, European Southern Observatory-La Silla; SAAO, South African Astronomical Observatory; SSO, Siding Spring Observatory.<sup>b</sup>Signal-to-noise ratio was measured in the continuum at ~5900 Å. When no signal-to-noise ratio is indicated this means that the continuum was not detected.

the CSPN. In addition, 10 previously known PNe were serendipitously discovered to possess [WR] CSPN in the course of general MASH follow-up observations with the AAO spectrograph (Saunders et al. 2004) on the Anglo-Australian Telescope and the 6dF spectrograph (Parker, Watson & Miziarski 1998) on the UKST. The object of observing missions with these wide-field multi-object spectrographs was to confirm as many MASH PNe as efficiently as possible. These multi-object spectrograph (MOS) instruments possess 400 and 150 fibres over a  $2^\circ$  and a  $6^\circ$  field, respectively. This enables us to place individual fibres not just on the primary MASH candidate objects but also on all other known PNe that are present in the field. Subsequently, during the long exposure times required to obtain sufficient signal-to-noise ratio in observations of the faint MASH PNe, the faint [WR] features of some central stars of previously known PNe also emerged. For a description of the AAO observations, see Misiarowski et al. (2009a).

Spectra of most of the 32 [WR]/WELS central stars presented here are to be found in Figs 3–5.

### 3 CLASSIFICATION SCHEMES

Wolf-Rayet central stars of PNe are divided into [WC] (carbon-sequence), [WO] (oxygen-sequence) and now a putative intermediate [WN/WC] class (e.g. PB8; Todt et al. 2010). LMC-N66 (Peña 1995) and PM 5 (Morgan et al. 2003) have also been classed as [WN] types, which differ from the [WN/WC] class only in carbon depletion. However, PM5 may also be a massive WR ring nebula (Frew & Parker 2010a). It should be noted that [WO] and [WC] types are named according to their most prominent lines and not because of any significant difference in chemical abundances (Crowther et al. 1998). The existence of the [WN/WC] and [WN] classes is still controversial.

The [WC] and [WO] subtype classifications are assigned according to the scheme of Crowther et al. (1998; hereafter CDB98) and the system devised by Acker & Neiner (2003; hereafter AN03). CDB98 refined the WO and WC schemes used for massive stars, and proposed a unified classification system for both massive WRs and [WR]s. AN03 extended the CDB98 criteria to a larger spectral range. AN03 constructed a grid of selected line-intensities ordered by decreasing ionization potential going from 871 to 24 eV. In this grid, the stars appear to belong clearly to prominent O (hot [WO1–4] types) or C (cooler [WC4–11] types) line-sequences, in agreement with the classification of massive WR stars applied to CSPNe. AN03 used 20 selected line ratios and the FWHM of C IV and C III lines as classification diagnostics.

Both classification schemes emphasize the identification of the C IV doublet at 5801 and 5812 Å. This doublet should be a broad feature ( $EW > 10$  Å) arising from the rapid expansion of the hot stellar wind. When the doublet has a small equivalent width and the 4650 Å N III/C III–IV complex is present in a spectrum, the central star may be classified as an WELS (Tylenda et al. 1993; Marcolino & de Araújo 2003). These objects generally have narrower lines than [WR]s and are highly ionized, sometimes to such a degree that the C IV  $\lambda\lambda 5801,12$  doublet is present but the C III  $\lambda 5696$  line is not (Tylenda et al. 1993). Because the C IV lines are so weak, they are often resolved into the separate components at 5801 and 5812 Å. There also exists a ‘very late’ (VL) classification for those [WC] stars that would meet the [WC11] criteria and also exhibit a C II  $\lambda 7236$  line (Górny et al. 2009). These objects generally reside in low-ionization PNe.

For a more precise [WR] classification, various C and O lines must be measured and their dereddened equivalent width or flux

ratios determined. However, the majority of these features are relatively weak, often leaving the exact subclass indeterminate in the absence of reasonably high S/N spectra. Deeper observations will be required to identify the exact spectral type for the majority of our newly discovered [WR] central stars.

In this paper each object’s classifications according to the CDB98 and AN03 schemes are listed in Table 2. Classifications in the two schemes generally agree, though one scheme is sometimes more precise than the other. The [WC] classification in both the schemes depends primarily on the presence of the C IV  $\lambda\lambda 5801,12$  doublet and the C III  $\lambda 5696$  line. Other lines, namely O VI  $\lambda\lambda 3811,34$  and O VII  $\lambda 5670$ , are necessary for classification as a [WO] star. See CDB98 and AN03 for example spectra for each subclass.

### 4 INDIVIDUAL OBJECTS

Below we provide details of the spectra of the new [WR] CSPNe, separated into those discovered in MASH PNe and in other previously known PNe. See Table 1 for observation details and Table 2 for [WR] classification, morphology and photometric data. Images of the MASH [WR]s and [WR] candidates taken from the AAO/UKST H $\alpha$  Survey and the SuperCOSMOS Sky Survey (Hambly, Irwin & MacGillivray 2001; Parker et al. 2005) can be seen in Fig. 1. Those of the non-MASH [WR] objects can be seen in Fig. 2.

#### 4.1 New [WR] stars

In this section we briefly detail the characteristics of the [WR] central stars of our PN sample, ordered by increasing Galactic longitude.

##### 4.1.1 PHR 1811–3042

The [WR] nature of the CSPN of PHR 1811–3042 was discovered during general MASH candidate follow-up service time on the AAO system at the Anglo-Australian Telescope. C IV  $\lambda\lambda 4658,7726$ ; O IV  $\lambda 7032,53$ ; O VI  $\lambda\lambda 3811,5290$  and He II  $\lambda\lambda 4686,5411$  are visible in the spectrum presented by Sharp et al. (2006). The C III  $\lambda 5696$  line is not evident. The prominent oxygen spectrum and high ionization stage of all lines suggests that this star is a [WO]. However, the C IV doublet at  $\lambda\lambda 5801,12$  is not visible, likely due to the absence of a continuum in that spectral region. The impossibility of measuring the doublet means that we cannot classify this star further. In this and other stars, high ionization lines of Ne VII and Ne VIII (see Fig. 3) can be identified, a more plausible identification than O VII and O VIII, because neon can be ionized (Werner, Rauch & Kruk 2007).

##### 4.1.2 BMP 1827–1504

BMP 1827–1504 was mentioned in Condon, Kaplan & Terzian (1999) as a candidate PN and was confirmed in MASH-II. We have only observed the spectral ranges 3960–5007 and 5700–8000 Å (Figs 3–5). The C IV  $\lambda\lambda 5801,12$  doublet appears to be the only stellar feature in the spectrum; it is weak but broad. The continuum of the spectrum is undetected, which means that the absence of a line does not mean that the line is not present. In addition, C III  $\lambda 5696$  resides in an unobserved part of the spectrum. We can therefore not carry out the usual comparison between the nearby C III  $\lambda 5696$  and C IV  $\lambda\lambda 5801,12$ , which even in the absence of a continuum can give an indication of the ionization state of the star. Only a general [WR] classification can be assigned at this stage pending further follow-up.

**Table 2.** A list of the newly discovered [WR] CSPNe, along with WELS found in the course of examining the sample. The top portion lists all of those PNe from the MASH sample, while those objects below the line are for previously known PNe.

| PN G       | Name                      | Subclass <sup>a</sup><br>(CDB98) | Subclass <sup>a</sup><br>(AN03) | Morph. <sup>b</sup> | Sample <sup>c</sup> | c(H $\beta$ ) | V                 | I      | J      | K <sub>S</sub> | Phot.<br>source <sup>d</sup> |
|------------|---------------------------|----------------------------------|---------------------------------|---------------------|---------------------|---------------|-------------------|--------|--------|----------------|------------------------------|
| 001.2–05.6 | PHR1811–3042              | [WO]                             | [WO1-2]                         | E                   | M-I                 | 1.37          | –                 | –      | –      | 12.28          | U                            |
| 016.8–01.7 | BMP1827–1504              | [WR]:                            | [WR]                            | R                   | M-II                | 3.69          | –                 | 15.41  | 14.46  | 13.03          | D                            |
| 037.7–06.0 | MPA1921+0132              | ≤[WC8]                           | [WC4]:                          | R                   | M-II                | 1.17          | 16.6              | 17.30  | >15.83 | 14.89          | N                            |
| 216.0+07.4 | PHR0723+0036              | [WC4]:                           | [WC4]:                          | E                   | M-I                 | 0.32          | 13.9              | 13.97  | 13.90  | 13.83          | D84,F08                      |
| 222.8–04.2 | PHR0654–1045              | [WC7]                            | [WC8]                           | E                   | M-I                 | 1.13          | 14.1              | 13.02  | 12.28  | 11.65          | N,D                          |
| 284.2–05.3 | PHR1001–6152              | ≤[WC4]                           | [WO3]                           | R                   | M-I                 | 1.11          | 16.4              | –      | 16.21  | –              | N,G                          |
| 297.0+06.5 | BMP1209–5553              | [WO1]:                           | [WO2]:                          | B                   | M-II                | 0.38          | –                 | –      | –      | –              | –                            |
| 302.0–01.6 | MPA1243–6428              | ≥[WC9]                           | [WC9]:                          | S                   | M-II                | 2.71          | –                 | 16.74* | 14.84  | 12.61          | D                            |
| 309.8–01.6 | MPA1354–6337              | ≤[WC7]                           | [WC4]:                          | E                   | M-II                | 2.85          | –                 | 17.00  | 14.97  | 13.50          | G                            |
| 313.4+06.2 | MPA1405–5507              | ≤[WC5]/WELS                      | WELS                            | S                   | M-II                | 0.37          | 15.8              | –      | 15.57  | 14.76          | N,G                          |
| 313.9+02.8 | PHR1416–5809              | [WC9]                            | [WC9]                           | E                   | M-I                 | 1.79          | 16.2              | 14.97* | 13.74: | 12.74          | N                            |
| 331.8–02.3 | MPA1624–5250              | WELS                             | WELS                            | R                   | M-II                | 1.88          | 16.5              | 15.96* | 14.26  | 12.16          | N,D                          |
| 336.5+05.5 | MPA1611–4356              | [WC/O4]:                         | [WO4]                           | R                   | M-II                | 0.80          | 17.4              | 17.12* | 16.36  | 15.64          | N,G                          |
| 348.4+04.9 | MPA1655–3535              | ≥[WC10]                          | [WC10]                          | S                   | M-II                | 1.34          | 16.4 <sup>e</sup> | 15.65  | 14.66  | 13.17          | N,G                          |
| 355.9–04.4 | PHR1753–3443 <sup>f</sup> | ≤[WC4]                           | [WO3]:                          | B                   | M-I                 | 2.36          | 15.7              | –      | 13.22  | 12.09          | G                            |
| 356.0–04.2 | PHR1753–3428              | ≤[WC4]                           | [WO2-3]                         | E                   | M-I                 | 2.20          | 17.8              | –      | –      | –              | G                            |
| 356.8–03.6 | PHR1752–3330              | EL                               | [WC11]                          | E                   | MU                  | 1.32          | 14.4              | 14.32  | 13.28  | 12.83          | N,D                          |
| 359.8+03.5 | PHR1731–2709              | ≤[WC8]                           | [WC4]:                          | E                   | M-I                 | 3.31          | –                 | –      | –      | –              | –                            |
| 000.7–02.7 | M2–21                     | WELS                             | WELS                            | R                   | SEC                 | 0.60          | 13.2              | –      | 13.20  | 12.02          | N                            |
| 003.9–02.3 | M1–35                     | WELS:                            | WELS                            | R                   | SEC                 | 1.36          | 15.1              | 14.66  | 12.95  | 11.87          | N,D                          |
| 008.1–04.7 | M2–39                     | WELS                             | WELS                            | R                   | SEC                 | 1.67          | 13.7 <sup>†</sup> | 14.51  | 13.53  | 12.04          | N,D                          |
| 008.2–04.8 | M2–42                     | WELS:                            | WO::                            | E                   | SEC                 | 2.40          | 15.2              | 15.29  | 14.45  | 13.53          | N,D                          |
| 029.0+00.4 | Abell 48 <sup>g</sup>     | –                                | WC::                            | E                   | SEC                 | 3.02          | 17.7              | 15.50  | 13.51  | 12.33          | N,D                          |
| 270.1–02.9 | Wr 17–23                  | ≤[WC7]                           | [WC5-6]                         | E                   | SEC                 | 2.51          | 16.7              | 16.48* | 13.97  | 12.27          | G                            |
| 322.4–00.1 | Pe 2–8                    | [WR]/WELS                        | WELS                            | E                   | SEC                 | 2.96          | 17.3              | 14.80* | 11.81  | 9.96           | G                            |
| 355.4–04.0 | Pe 1–10                   | [WO]:                            | [WO2]                           | E                   | SEC                 | 1.63          | –                 | –      | –      | –              | –                            |
| 356.1+02.7 | Th 3–13                   | [WC6-7]                          | [WC5-6]                         | R                   | SEC                 | 3.59          | –                 | 16.14  | 13.67  | 11.95          | D                            |
| 356.9+04.4 | M3–38                     | WELS                             | WELS                            | R                   | SEC                 | 1.78          | 17.2              | 15.74* | 13.97  | 12.52          | N,D                          |
| 357.4–03.2 | M2–16                     | ≤[WC4]                           | [WO2-3]                         | E                   | SEC                 | 0.80          | 16.5              | 15.18  | 13.68  | 12.56          | S08                          |
| 358.0–04.6 | Sa 3–107                  | WELS                             | WELS                            | R                   | SEC                 | 1.43          | 16.4              | 15.80  | –      | –              | G                            |
| 358.9+03.3 | H1–19                     | WELS                             | WELS                            | R                   | SEC                 | 2.04          | 17.1              | 14.63  | 12.39  | 11.05          | N,D                          |
| 359.9–04.5 | M2–27                     | ≤[WC8]:                          | [WC4]:                          | R                   | SEC                 | 0.94          | 14.4 <sup>†</sup> | 14.32  | 12.93  | 11.78          | D                            |

<sup>a</sup>[WR] subclasses are very approximate because of the modest quality of our spectra. Where ‘WELS’ is indicated, this object fails the respective [WR] subclass scheme and meets the criteria listed in Section 3 for that class. ‘EL’ indicates that emission lines at WR wavelengths were seen, but the object does not meet the other criteria for [WR] classification.

<sup>b</sup>B, bipolar; E, elliptical; I, irregular; R, round; S, quasi-stellar.

<sup>c</sup>M-I, MASH-I (Parker et al. 2006); M-II, MASH-II (Miszalski et al. 2008a); MU, Found in the MASH sample but previously unpublished; SEC, PN previously known from Strasbourg–ESO Catalogue (Acker et al. 1992).

<sup>d</sup>J and K<sub>S</sub> magnitudes are from 2MASS (Skrutskie et al. 2006) unless otherwise indicated. N, NOMAD-I (Zacharias et al. 2004); G, GSC 2.3.2 (Lasker et al. 2008); D, DENIS (Epchtein et al. 1994); D84, Downes (1984); F08, Frew (2008); S08, Sabogal et al. (2008); U, UKIDSS (Lawrence et al. 2007).

<sup>e</sup>V magnitude given as 13.1 in Wackerling (1970). This measurement is probably contaminated by a nebular component.

<sup>f</sup>Also called K 6-32 in Kohoutek (2002). See Section 4.1.16.

<sup>g</sup>Probable [WN/WC]. See Section 4.1.3 for a discussion of the classification.

: Classification uncertain.

\*Mean of two observations.

<sup>†</sup>Nebular contamination.

#### 4.1.3 Abell 48

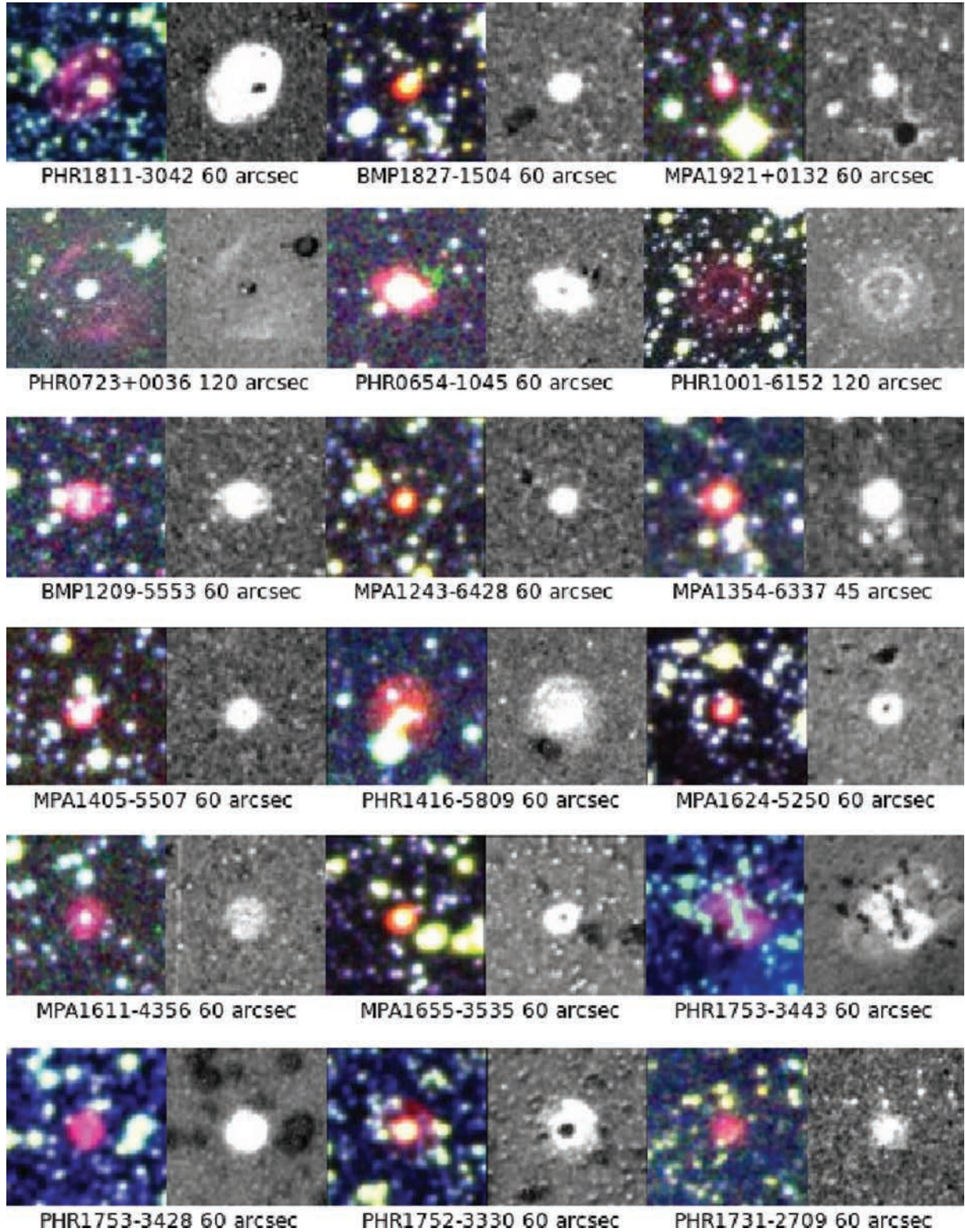
Abell 48 is a highly reddened PN that was discovered by Abell (1955, 1966). The central star exhibits a broad He II  $\lambda$ 4686 line and a strong, broad 7118-Å feature. Based on the presence of this feature, this could be mistaken for a [WC] in the AN03 scheme, but it is more likely a complex of six N IV lines between 7103 and 7129 Å if we take into account the recent WN identification of Wachter et al. (2010).

The CS of Abell 48 was recently designated as a massive WN6 star in Wachter et al. (2010), although our spectra predate this study. However, this object is more likely to be a PN than a massive WR ring nebula. Abell 48 may well be another member of the rare

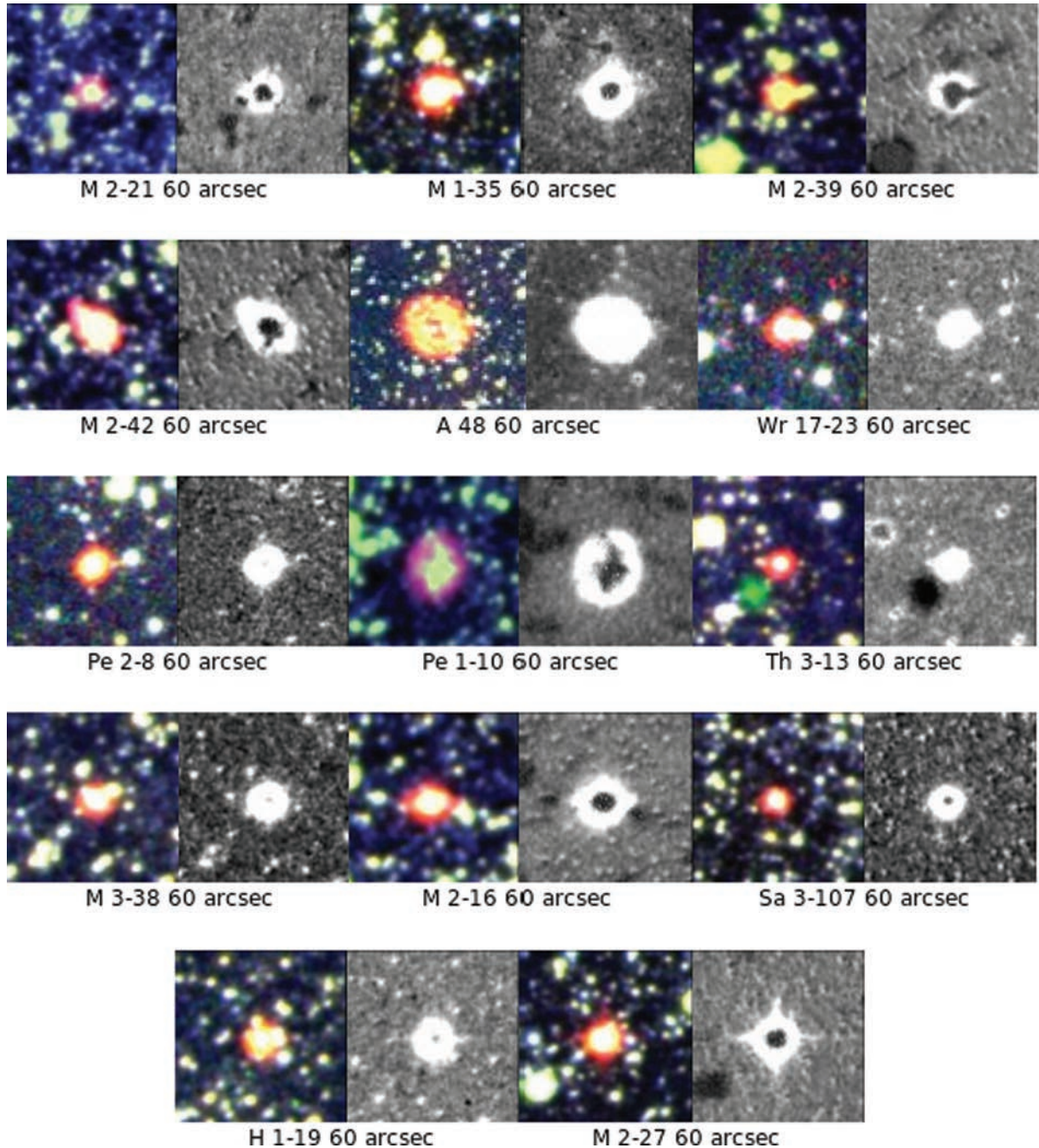
[WN] or [WN/WC] class mentioned in Todt et al. (2010). The arguments for this will be presented in a later paper (DePew et al., in preparation). The spectrum, coordinates and observation details of this object can be found in Fig. 5 and Tables 1 and 2. Abell 48 has been previously studied in the IR wavelengths by Phillips & Ramos-Larios (2008). It is a clear detection in GLIMPSE (Cohen et al. 2011).

#### 4.1.4 MPA 1921+0132

MPA 1921+0132 exhibits a broad C IV  $\lambda$ 5801,12 doublet (Fig. 4) typical of the [WR] class. There is a broad, weaker feature centred around 4665 Å which may contain C IV  $\lambda$ 4658 and He II  $\lambda$ 4686.



**Figure 1.** A montage of the new MASH [WR] and WELS PNe, ordered according to Galactic longitude. Each  $H\alpha$ /SR/ $B_J$  composite colour image is accompanied by the  $H\alpha$ /short-red quotient image to its right. The  $H\alpha$ /SR images are from the SuperCOSMOS  $H\alpha$  Survey (Parker et al. 2005) and the  $B_J$  images from Hambly et al. (2001). The lengths of the image sides in arcseconds are presented alongside the name of each object. North is to the top and east is to the left for all images.



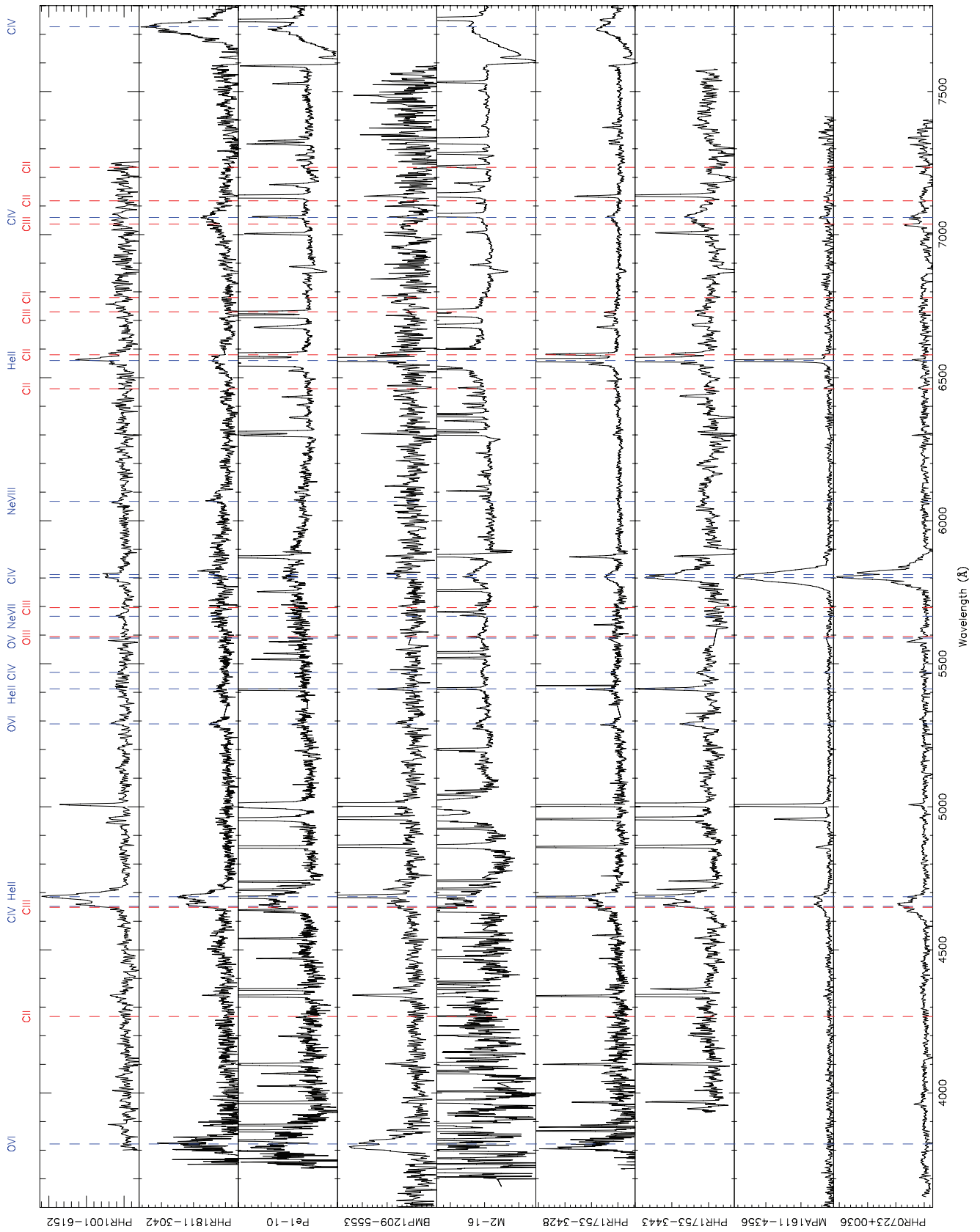
**Figure 2.** A montage of the non-MASH PNe found to contain a true or candidate [WR] or WELS central star. As in Fig. 1, each  $H\alpha$ /SR/ $B_J$  composite colour image (Hambly et al. 2001; Parker et al. 2005) is accompanied by the  $H\alpha$ /short-red quotient image to its right. Again, the lengths of the image sides in arcseconds are presented alongside the name of each object. North is to the top and east is to the left for all images.

The continuum of this entire spectrum is undetected. It is therefore impossible to determine if a line is truly absent. We can only assert that  $C_{III} \lambda 5696$  is weaker than  $C_{IV} \lambda \lambda 5801,12$ , making this an earlier spectral subtype than [WC8] in the CDB98 system.

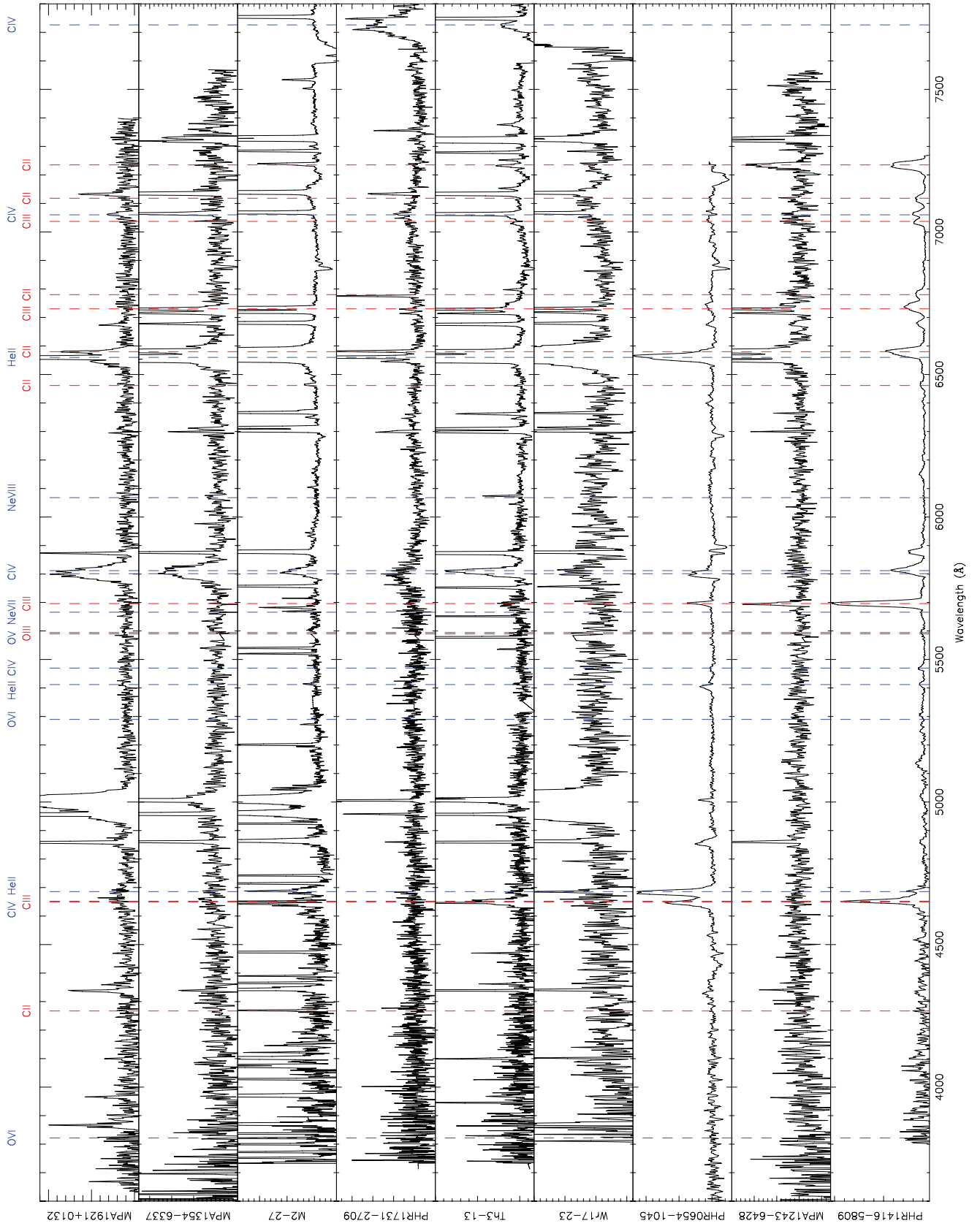
#### 4.1.5 PHR 0723+0036

The relatively bright central star of this PN was originally identified as a WC star by Downes (1984), who named it KPD 0721+0042. Downes (1984) noted that the two strongest features in the spectrum of KPD 0721+0042 are the  $C_{IV}$  lines. He found no evidence

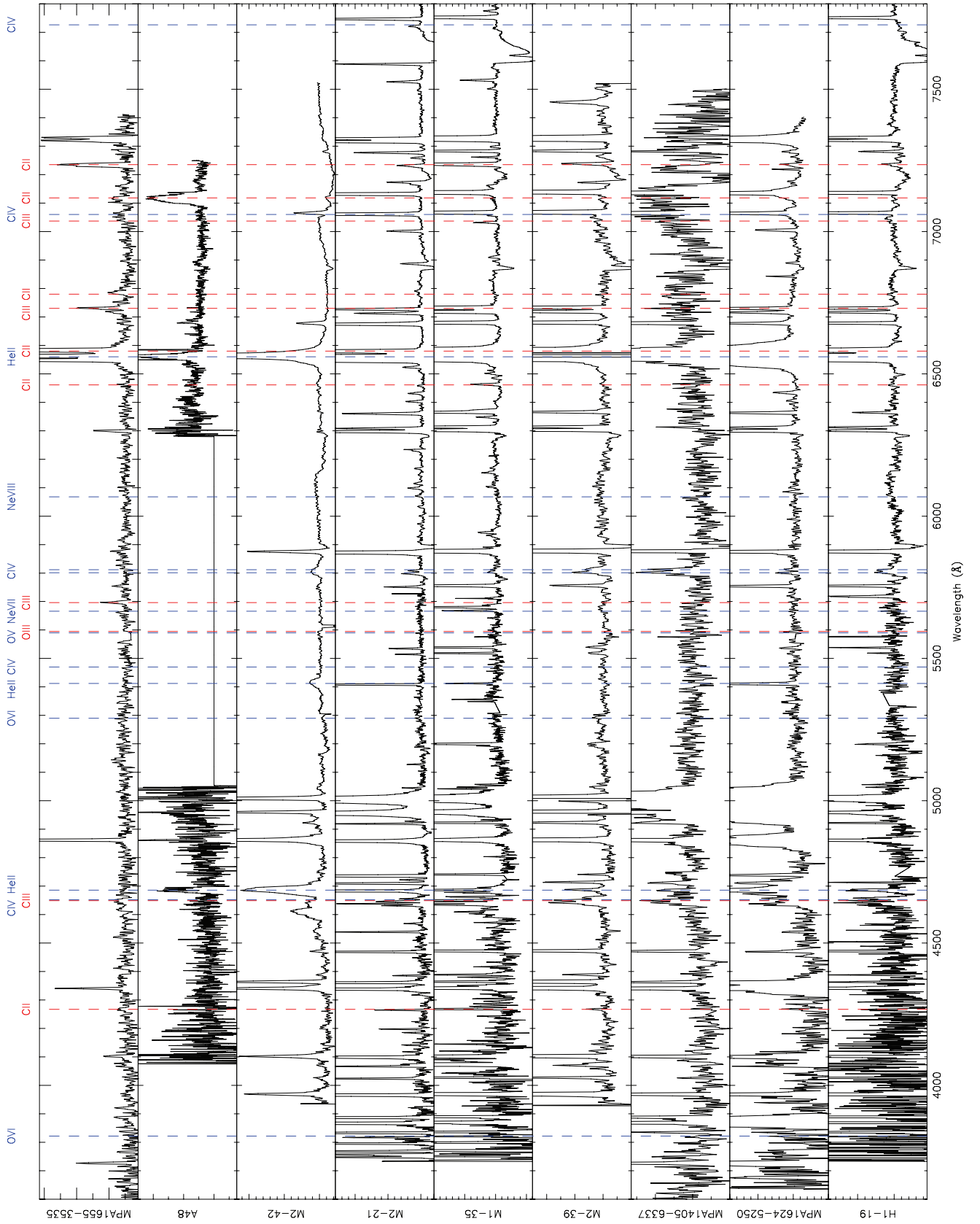
of  $C_{III} \lambda 5696$  emission, and consequently classified this object as WC4 following van der Hucht et al. (1981). Downes (1984) found the strength of the  $N_{III} \lambda 4634$  line to be ‘unprecedented for any WC star’. Furthermore, the estimated distance of 1200 pc above the Galactic plane argued for halo membership, leading Downes to theorize that this was actually a Population II WC star, though he detected no nebular features from any associated nebula. The surrounding PN was finally uncovered by the MASH survey, indicating that the star is indeed a [WR]. The  $C_{IV} \lambda \lambda 5801,12$  doublet in our spectrum (Fig. 4) has an EW of  $\sim 70 \text{ \AA}$ . The feature around  $\lambda 4650$  is very broad, likely comprising  $C_{IV} \lambda 4658$  and  $He_{II} \lambda 4686$ . The



**Figure 3.** Spectra of objects whose central stars have recently been identified as being [WR]s or WELS; all spectra have been rectified. The most prominent lines have been identified (dashed lines and labels).



**Figure 4.** Spectra of objects whose central stars have recently been identified as being [WR]s or WELS; all spectra have been rectified. The most prominent lines have been identified (dashed lines and labels).



**Figure 5.** Spectra of objects whose central stars have recently been identified as being [WR]s or WELS; all spectra have been rectified. The most prominent lines have been identified (dashed lines and labels).

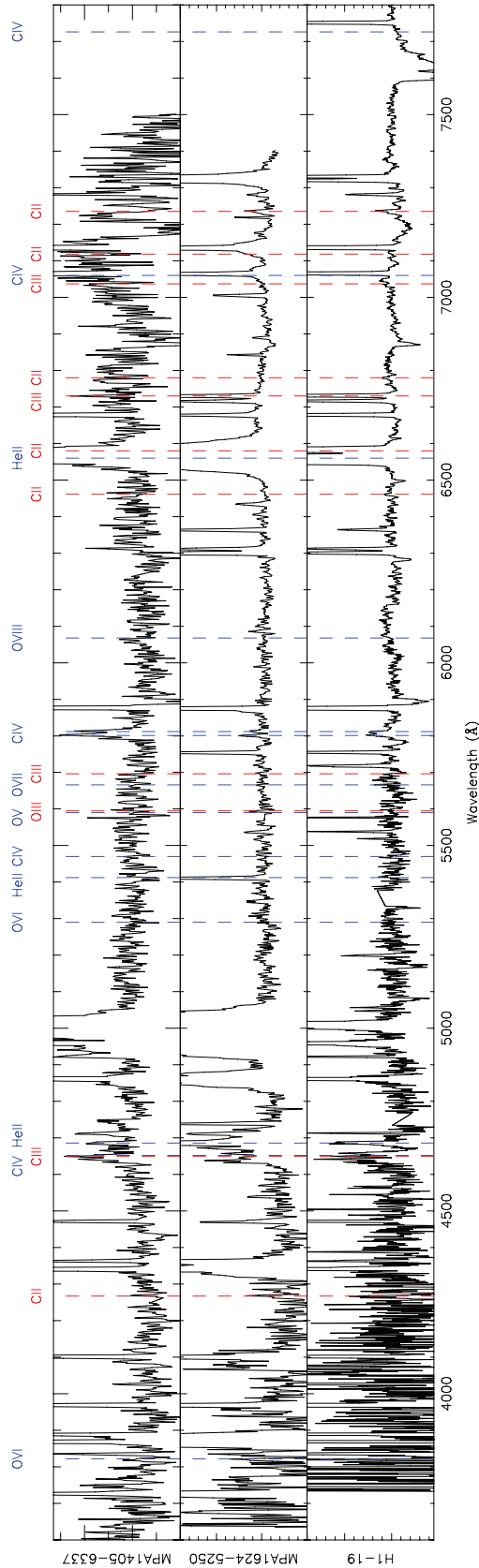


Figure 5 – continued

continuum is evident. Given the absence of C III  $\lambda 5696$  and oxygen emission lines, this star is likely a [WC4] in the CDB98 system.

Given the intensity of the C IV/He II blend at  $\sim 4650$  Å [ $\sim 0.5$  of  $F(\lambda\lambda 5801,12)$ ] and the absence of C III  $\lambda 5696$ , we confirm a [WC4] classification according to the AN03 scheme.

#### 4.1.6 PHR 0654–1045

PHR 0654–1045 was first mentioned as a possible PN (PM1–23) by Preite-Martinez (1988) based on IRAS photometry. It was similarly classified as a PN candidate by García-Lario et al. (1990) who designated it as GLMP 160. The object was unambiguously shown to be a PN in the MASH catalogue (Parker et al. 2006) based on spectroscopic confirmation in 2003 January, where the [WR] CSPN features were first noted. The CSPN was subsequently included in Acker & Neiner (2003). Pereira & Machado (2003) independently noted [WR] features in the CSPN classifying it as a [WC6-7] star according to the CDB98 scheme. It is also listed in the catalogue of Suárez et al. (2006) as a [WC7].

Based on our data the central star exhibits the strong C IV doublet  $\lambda\lambda 5801,12$  with  $EW \sim 7$  Å, as well as a strong C III  $\lambda 5696$  line with  $EW \sim 4$  Å, implying an approximate classification of [WC7] according to the CDB98 scheme (see Figs 3–5). This object displays a prominent He II line at 4686 Å. O VI  $\lambda\lambda 3811,34$  are absent. The strong broad feature at the wavelength of H $\alpha$  might be partly due to stellar He II. The FWHM of the C IV doublet ( $\sim 25$  Å) is within the range of the [WC7] spectral subtype in the CDB98 scheme. The C III  $\lambda 4650$  line appears to be approximately 3.5 times as intense as the C IV  $\lambda\lambda 5801,12$  doublet. The intensity of the C III  $\lambda 5696$  line ( $\sim 0.45$  of the C IV doublet) and the width of the C IV  $\lambda\lambda 5801,12$  doublet also argue for a [WC8] according to the AN03 scheme.

Hajduk et al. (2010) have recently found this star to be a photometric variable with a period of 0.63 d, possibly indicating a close binary. This would be the only currently known [WR] star to have passed through a common envelope phase. These authors also classified the CS as [WC7].

#### 4.1.7 Wray 17–23

This PN was originally found by Wray (1966) and is noted in the catalogue of Suárez et al. (2006) as IRAS08574–5011. Ionized oxygen species seem lacking from the spectra of the central star that we have obtained (see Figs 3–5). The C IV  $\lambda\lambda 5801,12$  doublet is weak and broad ( $EW \sim 25$  Å,  $FWHM \sim 50$  Å), but C III  $\lambda 5696$  is not visible. Since the continuum is barely detected, we estimate that the C III  $\lambda 5696$  line has to be weaker than  $\sim 50$  per cent of the C IV doublet. This suggests that this object has a spectral type of [WC7] or earlier according to CDB98 and [WC5–6] in the AN03 system. [O III]  $\lambda\lambda 4959,5007$  project from broad pedestals due to scattered light in the instrument.

#### 4.1.8 PHR 1001–6152

The C IV  $\lambda\lambda 5801,12$  doublet is present. The He II  $\lambda 4686$  line is very prominent in the central star's spectrum (Figs 3–5); He II  $\lambda 5411$  is not readily apparent. O VI  $\lambda\lambda 3811,34$  is not apparent, but the continuum in this region is too noisy to conclude that the line is absent. C III  $\lambda 5696$  is not evident. The absence of C III  $\lambda 5696$  and the width of the C IV  $\lambda\lambda 5801,12$  doublet would argue for a [WC4] subtype or earlier in the CDB98 scheme. However, the C IV  $\lambda\lambda 5801,12$  line ( $EW \sim 10$  Å) marks this object as having an unusually weak lined spectrum. We refrain from designating it a

WELS because the C IV doublet is far broader than normal for this class (Marcolino & de Araújo 2003).

The He II  $\lambda 4686$  line is almost three times as intense as the C IV  $\lambda\lambda 5801,12$  doublet, but this is due more to the weakness of the doublet. The possible O VI  $\lambda 5290$  line is  $\sim 0.6$  times the strength of the C IV doublet, but this measurement is very uncertain. Based on the strengths of the He II  $\lambda 4686$  line and C IV  $\lambda 4658$  line, and the apparent absence of the high-excitation O VI  $\lambda 3822$  doublet, this star is classified as a [WO3] in the AN03 scheme.

#### 4.1.9 BMP 1209–5553

The central star of BMP 1209–5553 shows a very strong O VI  $\lambda\lambda 3811,34$  doublet (Fig. 3), which, along with the emission blend at 4650 Å, comprise the strongest stellar features seen in this spectrum. The blend likely comprises C IV  $\lambda 4658$  and He II  $\lambda 4686$ , the latter of which appears to possess a nebular component. This star may exhibit a weak C IV  $\lambda\lambda 5801,12$  feature. The continuum is not observed for this star. Based on the strength of the O VI  $\lambda 3811$  line, which is much stronger than both C IV  $\lambda\lambda 5801,12$  and O V  $\lambda 5590$ , this star is likely a [WO1] in the CDB98 system, while based on the strength of He II  $\lambda 4686$  and O VI  $\lambda 3811$ , and the weakness of C IV  $\lambda\lambda 5801,12$ , this is a [WO2] in the AN03 system.

#### 4.1.10 MPA 1243–6428

The C III  $\lambda 5696$  and C II  $\lambda 7236$  lines are prominent (Fig. 5), while C IV  $\lambda\lambda 5801,12$  are not observed. C II  $\lambda 4267$  is in an extremely noisy part of the spectrum, so we cannot conclude that it is absent. However, the continuum is not observed, so we cannot guarantee that C IV is not present. Since C III  $\lambda 5696$  is clearly much stronger than C IV  $\lambda\lambda 5801,12$ , we can deduce that this star has a later subtype than [WC9] in the CDB98 scheme and approximately [WC9] in the AN03 one. Helium lines are absent. The Balmer lines are present, but the nebular [O III] lines are not. In [WC9–11]s, the ionization of the PN would be low, so this is to be expected.

#### 4.1.11 MPA 1354–6337

The broad C IV  $\lambda\lambda 5801,12$  doublet is strong (Fig. 4). The C III  $\lambda 5696$  line is not visible. However, since the continuum is not detected, we can only say that this star has a spectral type earlier than [WC7] according to CDB98. Because the C IV doublet is in any case more intense than C III  $\lambda 5696$ , this star must be approximately a [WC4] in the AN03 system.

#### 4.1.12 PHR 1416–5809

This central star has strong C III  $\lambda 5696$ , C IV  $\lambda 4658$  and He II  $\lambda 4686$ . The C III  $\lambda 5696$  line has an intensity over twice that of the C IV doublet, indicating that this object is a [WC9] in both CDB98 and AN03 schemes.

#### 4.1.13 MPA 1611–4356

MPA 1611–4356 first appeared in Miszalski et al. (2008a). The central star displays a strong, broad C IV  $\lambda\lambda 5801,12$  doublet, with an FWHM of  $\sim 40$  Å and an EW of  $\sim 600$  Å (Figs 3–5). This is easily the strongest stellar feature in the spectrum. He II  $\lambda 4686$  is heavily blended with the C IV  $\lambda 4658$  line. This object has a low signal-to-noise ratio but the strength of C IV  $\lambda\lambda 5801,12$ , absence of C III  $\lambda 5696$  and presence of the C IV–He II blend at  $\sim 4670$  Å argues for a [WC4] or a [WO4] classification. In a [WC/O4] the C IV–He II

blend is stronger compared to C IV  $\lambda\lambda 5801,12$ ; however, the lack of a continuum detection in the blue makes the bluer of the two features artificially weak. Yet it is strange that the He II  $\lambda 4686$  line appears stronger than C IV  $\lambda 4658$  in this star. This is the opposite of what is expected in a normal [WC/O4] (see Crowther et al. 1998).

#### 4.1.14 MPA 1655–3535

This object was classified as an early-type emission-line star by Wackerling (1970), but the surrounding PN was not discovered until the MASH survey, likely owing to its compact nature. C III  $\lambda 5696$  is detected (Fig. 5), as is a possible C II  $\lambda 4267$  line ( $\sim 0.8$  times the intensity of C III  $\lambda 5696$ ). C IV  $\lambda\lambda 5801,12$  is absent. Considering that the continuum signal-to-noise ratio is extremely low, we classify the star as later than a [WC10] in the CDB98 scheme (the C IV  $\lambda\lambda 5801,12$  doublet could be 1/10th of the intensity of C III  $\lambda 5696$  and be lost in the continuum noise). There is no nebular [O III]  $\lambda 5007$  line, which, when combined with its small, compact nature and its Galactic latitude, indicates that this is a very low-excitation PN containing a cooler central star.

Given the strong C II  $\lambda 7236$  line, this is probably later than a [WC10] in the AN03 system.

#### 4.1.15 Pe 1–10

Pe 1–10, also known as Hf2–1, was first mentioned in Perek (1960). Miszalski et al. (2009b) presented an AAS spectrum of the central star which clearly showed broad, relatively strong emission features at O VI  $\lambda\lambda 3811,34$  and around He II  $\lambda 4686$ , indicating a [WO] classification. This latter feature is likely blended with C IV  $\lambda 4658$ . Narrow nebular lines at He II  $\lambda\lambda 4686,5411$  and He I  $\lambda 5876$  are visible. Broad weaker stellar C IV features may be present around 5806 and 7726 Å. This star was also observed by Górny et al. (2009) but their long-slit spectra either missed the CSPN or were too shallow to reveal the [WO] features.

#### 4.1.16 PHR 1753–3443

This PN is now also known as PN K6–32 (see Kohoutek 2002), but the MASH discovery and spectrum of the central star predates its publication in that catalogue.

While C IV  $\lambda\lambda 5801,12$  is present (EW  $\sim 12$  Å), C III  $\lambda 5696$  is not; this CS is probably hotter than [WC4] in the CDB98 classification. C IV  $\lambda 4658$  is detected, while He II  $\lambda 4686$  has a nebular component. The width of the C IV line is narrower than typical for a [WC4].

O VI  $\lambda 5290$  appears to be present ( $\sim 0.57$  of C IV  $\lambda\lambda 5801,12$ ), as is C IV  $\lambda 7060$  ( $\sim 0.17$  of C IV  $\lambda\lambda 5801,12$ ) suggesting that this is a [WO3] according to AN03.

#### 4.1.17 PHR 1753–3428

The C IV  $\lambda\lambda 5801,12$  doublet is relatively strong. The C IV–He II blend at 4650 Å is also present. There is no C III  $\lambda 5696$ , so this star is earlier than [WC4]. As is the case for PHR 1753–3443, the FWHM of the C IV  $\lambda\lambda 5801,12$  is rather narrow for an early [WC] star.

#### 4.1.18 Th 3–13

Th 3–13 is listed as a WELS PN in Górny et al. (2004). However, our spectrum presents a strong and broad C IV  $\lambda\lambda 5801,12$  feature. The C III  $\lambda 5696$  feature is shallow but approximately as broad as the C IV doublet. The intensity ratio of the C IV doublet to the C III  $\lambda 5696$  line ( $\sim 3.9$ ) falls within the range delineated for [WC6–7]s

in the CDB98 scheme, although the width of the doublet is low for that class. The  $C_{II} \lambda 4267$  line is not visible, but this may be due to reddening, which is large in this object [ $c(H\beta) = 3.6$ ].

The  $C_{III} \lambda 5696$  line is 0.27 times as intense as the  $C_{IV}$  doublet and the  $C_{III-IV} \lambda 4650$  blend is almost three times the value of the doublet, suggesting a classification of [WC5–6] in the AN03 scheme.

#### 4.1.19 PHR 1752–3330

The  $C_{IV} \lambda \lambda 5801,12$  doublet is absent, as is  $C_{II} \lambda 4267$ .  $C_{III} \lambda 5696$  is present, as is  $C_{II} \lambda 7236$ , but both are very weak and narrow. A system of absorption lines appears at  $\sim 5800 \text{ \AA}$  as well as  $\sim 4650 \text{ \AA}$ . In the CDB98 scheme, this object cannot be classified as a late [WC] because the  $C_{III}$  line at  $5696 \text{ \AA}$  is too weak and both  $C_{IV} \lambda \lambda 5801,12$  and  $C_{II} \lambda 4267$  are lacking. CDB98 would call this an emission-line star. Due to the absorption line at  $He_{II} \lambda 5411$ , this is a [WC11] according to the AN03 scheme.

#### 4.1.20 M2–16

This PN is listed as a non-emission-line star in Gesicki et al. (2006). However, the central star is classified as a variable Be candidate by Sabogal et al. (2008), though no further explanatory details are provided. A broad  $C_{IV} \lambda \lambda 5801,12$  doublet and  $C_{IV} \lambda 7726$ , as well as a possible  $O_{V} \lambda 5590$ , are detected. This is hotter than [WC4] in the CDB98 scheme.

#### 4.1.21 PHR 1731–2709

The [WR] character of the reddened central star of PHR 1731–2709 was originally overlooked in the PN confirmatory spectrum. More recent observations in 2008 May have uncovered a broad feature around  $C_{IV} \lambda \lambda 5801,12$  (Fig. 4).  $C_{IV} \lambda 7726$  is also detected (not shown in the figure). The lack of continuum detection allows us to say only that  $C_{IV} \lambda \lambda 5801,12$  is stronger than  $C_{III} \lambda 5696$ . Therefore, this star has an earlier type than [WC8] in the CDB98 system.

#### 4.1.22 M2–27

The CS of M2–27 was originally classified as a WELS in Górný et al. (2004). However, this object has a weak but broad ( $EW \sim 15 \text{ \AA}$ ,  $FWHM \sim 25 \text{ \AA}$ )  $C_{IV} \lambda \lambda 5801,12$  doublet in our spectra. Neither the oxygen excitation lines nor the  $C_{III} \lambda 5696$  line appear to be present, although  $C_{II} \lambda 7236$  is visible. Due to the weakness of  $C_{III} \lambda 5696$ , this is likely earlier than a [WC8] in the CDB98 scheme.

## 4.2 Possible [WR]s and WELS

In this section we briefly detail the spectra of several objects that may exhibit [WR] features, including WELS, but require deeper spectra to allow a proper classification.

#### 4.2.1 M2–21

M2–21 was first mentioned in Wray (1966), where it was designated Wr 16–337. The central star was designated a WELS in Górný et al. (2009), but our observations predate this publication. This object displays partially resolved  $C_{IV}$  doublet  $\lambda \lambda 5801,12$  lines and a  $N_{III}/C_{III-IV}$  complex at  $\lambda \lambda 4631,4641,4650$ .  $C_{III} \lambda 5696$  is absent, in line with a WELS classification. The presence of  $C_{II}$  lines is surprising, given the absence of  $C_{III}$  and the presence of  $C_{IV}$ , suggesting a different origin, possibly nebular.

#### 4.2.2 M1–35

M1–35 is a Type I bulge PN. Interestingly, it was observed by Górný & Siódmiak (2003), but no emission lines were found; however, we detect an emission-line spectrum. The  $N_{III}/C_{III-IV}$  complex around  $\lambda 4640$  is prominent. The lines appear to be narrow. The  $C_{IV} \lambda 5801,12$  doublet is a doubtful detection, but if present is very faint.  $C_{III} \lambda 5696$  is absent, so this is potentially a WELS. However, the weakness/absence of  $C_{IV} \lambda \lambda 5801,12$ , combined with the strength of the  $N_{III}/C_{III-IV}$  complex, potentially indicates an alternative identification as an irradiated close binary central star.

#### 4.2.3 M2–39

M2–39 is classified as a WELS in Górný et al. (2004) and is mentioned in Górný et al. (2009) as a low-metallicity PN. Our MASH observation of this object predates its publication in Górný et al. (2004).

The broad  $C_{IV}$  doublet has an FWHM of  $20 \text{ \AA}$  and an EW of  $5 \text{ \AA}$  (Fig. 5).  $C_{III} \lambda 5696$  is not visible.  $He_{II} \lambda 4686$  is present, but  $He_{II} \lambda 5411$  is not seen.  $N_{III} \lambda 4634$  and  $\lambda 4641$  are present alongside  $C_{III} \lambda 4650$  and  $C_{IV} \lambda 4658$ .

Based on the high ionization of this star, as well as the narrowness of the observed emission lines, this star is probably a WELS.

#### 4.2.4 M2–42

M2–42's  $C_{IV} \lambda 5801,12$  doublet lines are easily visible with an  $EW = 13 \text{ \AA}$ . However,  $C_{II} \lambda 4267$  and  $C_{III} \lambda 5696$  are not observed. The  $He_{II}$  lines at  $4686$  and  $5411 \text{ \AA}$  are relatively strong. We observe the  $4650\text{-\AA}$  line complex, although the identification of the specific lines is not certain. We fit two lines at  $\sim 4607$  and  $\sim 4641 \text{ \AA}$ , which could correspond to the  $N_{V} \lambda \lambda 4604,20$  doublet and  $N_{III} \lambda 4634,41$  doublet. Beyond these, there are no visible stellar lines. This object could be a WELS.

#### 4.2.5 MPA 1405–5507

The central star is classed as [WC4–6] in the MASH-II catalogue.  $C_{IV} \lambda \lambda 5801,12$  is present and  $He_{II} \lambda 4686$  is weak (Fig. 5), while  $C_{III} \lambda 5696$  is not visible. No oxygen lines are detected. The  $4650 \text{ \AA}$  emission complex is present.

The ratio of  $C_{IV} \lambda \lambda 5801,12$  to  $C_{III} \lambda 5696$  is likely larger than 10, making this an earlier spectral subtype than [WC5] in the CDB98 system. However, given the narrowness of the  $C_{IV} \lambda \lambda 5801,12$  and the lines in the  $\lambda 4650$  complex, this object could also be a WELS.

#### 4.2.6 Pe 2–8

This PN, originally noted in Perek (1960), has been previously observed by Dopita & Hua (1997) and Hora et al. (2008). In Hora et al. (2008), Pe 2–8 was observed in IR with *Spitzer* and used for comparison against several LMC PNe.

The stellar continuum is barely detected. The  $C_{IV}$  doublet exhibits separate peaks at  $5801$  and  $5812 \text{ \AA}$ . This raises the possibility of a WELS identification, although it must be noted that the EW of both peaks ( $12$  and  $12 \text{ \AA}$ , respectively) are larger than normal for WELS. We cannot speculate further since our spectral range does not contain the other diagnostic lines (e.g.  $C_{III} \lambda 5696$ ).

#### 4.2.7 MPA 1624–5250

The C IV  $\lambda$ 5801 and  $\lambda$ 5812 lines each have an equivalent width approximately equal to the instrumental resolution of 5 Å. C III  $\lambda$ 5696 is absent. There is a faint but visible N III/C III–IV complex around 4650 Å. This object is likely a WELS.

#### 4.2.8 M3–38

This object exhibits both C IV  $\lambda$ 5801 and  $\lambda$ 5812, but these lines are narrow and well separated. The C III  $\lambda$ 5696 line was not in the observed spectral range, but the prominent N III  $\lambda$ 4634 and  $\lambda$ 4641 lines indicate that this is a WELS.

#### 4.2.9 Sa 3–107

The individual peaks of the C IV  $\lambda\lambda$ 5801,12 doublet are visible, a characteristic of many late [WC]s and WELS. This doublet has an EW  $\sim 9$  Å, which is also a common characteristic of WELS. The C IV  $\lambda$ 7726 line is also present. O VI  $\lambda\lambda$ 3811,34 and C II  $\lambda$ 4267 are absent. C III  $\lambda$ 5696 is absent, which suggests that this star is not a late-type [WC], but a WELS.

#### 4.2.10 H1–19

H1–19 is a bulge object. Its chemical abundances have been previously examined in Chiappini et al. (2009). The central star exhibits a partially resolved C IV  $\lambda\lambda$ 5801,12 doublet and the N III/C III–IV complex at  $\sim 4640$  Å. In addition, C III  $\lambda$ 5696 is absent, indicating this to be a WELS.

## 5 CONCLUSIONS

32 new [WR] CSPNe, candidate [WR]s and WELS have been presented. 22 members in this sample are identified as probable [WR]s; the remaining 10 appear to be WELS. While 18 of these objects have been discovered in the MASH sample, 14 were found in previously known PNe through serendipitous fibre placement during follow-up observations of MASH objects with wide-field MOS systems such as AAΩ, 2dF and 6dF. This illustrates first and foremost that the central stars of more planetary nebulae should be observed. Estimates of the percentage of CSPNe known to exhibit WR features have in the past hovered around 7–9 per cent (Tylenda et al. 1993; Tylenda 1996; Acker & Neiner 2003; Frew & Parker 2010b). Hydrogen-deficient stellar evolution is still poorly understood, but its understanding may become more urgent if the proportion of stars which display this phenomenon grows. A survey of a large sample of CSPNe may help to place theoretical constraints on stellar evolution models.

Proper subclass designations will require deeper observations of the 32 CSPNe mentioned here. The spectra presented in this paper are preliminary, which necessitates a follow-up. A future paper will analyse the Galactic distribution and dynamical age of these newly discovered objects (DePew et al., in preparation).

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## APPENDIX A

Here we discuss five objects that possess interesting broad-lined spectra which we have discovered in the course of our analysis of the MASH data base. These objects were originally selected on the preliminary basis of having exhibited lines at or near [WR] wavelengths. On a deeper examination, they appear to lie outside the typical [WC]/[WO]/WELS classifications. Observation details are presented in Table A1.

## PHR 1757–1649

This is an unusual, high-excitation nebula with a quite irregular morphology. Our SHS images show a smaller limb-brightened, coherent elliptical shell in the NE portion, surrounding a prominent central star. We interpret this as a possible evolved PN embedded in a larger unrelated H II region, in turn ionized by UV photons leaking out of the optically thin PN shell. Our spectra of the central star show WN features. However, for any reasonable reddening, this object would be very remote ( $D > 10$  kpc) if the nucleus was a Population I WR star. The lack of warm dust seen in MSX images combined with the large  $z$  height at the assumed distance militates against an interpretation as a star-forming region. We hence conclude that this may be a PN around an H-deficient low-mass star, possibly a new member of the [WN] or [WN/WC] class. There appear to be no carbon lines, however, so we refrain from designating it as a probable [WR] star. Further observations are planned for this interesting object.

## MPA 1518–4738

The only features in the spectrum of this object are the broad He II  $\lambda 4686$ , H $\alpha$  and H $\beta$  lines. There is an emission blend at 4650 Å, which could be the N III, C III–IV complex. The continuum is not detected. The FWHM of H $\alpha$ , H $\beta$  and He II  $\lambda 4686$  are  $\sim 1400$  km s $^{-1}$  broader than the spectral resolution and much broader than would be expected of nebular lines, indicating a stellar origin.

## MPA 1602–5543

Our spectrum of this object is very poor; the one prominent line is a broad feature centred on 6558 Å. This may be a blend of [N II]  $\lambda\lambda 6548, 6584$ , He II  $\lambda 6560$  and/or H $\alpha$ . We refrain from classifying this star until better spectra are obtained.

## PHR 1603–5402

The emission-line star is part of a resolved triple star on SuperCOSMOS Sky Survey<sup>3</sup> images. The surrounding nebula was classified as a reflection nebula (GN 15.59.8) by Magakian (2003), but it appears to be a compact H II region holding a massive WR star. This would have to be a subclass earlier than WC8 considering the wide (FWHM  $\sim 130$  Å) C IV  $\lambda\lambda 5801, 12$  doublet and absence of C III  $\lambda 5696$ . The width of the C IV doublet would be typical of a WO2 star. It deserves follow-up observations.

## PPA 1702–3509

This appears to be a compact emission-line nebula with a 16th magnitude CS. There is enough of a discrepancy between the published visual magnitudes from GSC (Lasker et al. 2008) and NOMAD (Zacharias et al. 2004) and the DENIS (Epchtein et al. 1994) and 2MASS (Skrutskie et al. 2006) NIR photometry, to suggest that the CS may be variable. Indeed the spectral features are reminiscent of V Sge, the prototype of a very rare class of nova-like cataclysmic variables (Steiner & Diaz 1998) showing broad-line spectra. The V Sge stars show broad emission lines due to He II, O VI and N V. Our spectra do not go far enough to the blue to detect the O VI  $\lambda\lambda 3811, 34$

<sup>3</sup> <http://www-wfau.roe.ac.uk/sss/>

**Table A1.** Observation details of the objects listed in Appendix A.

| PN G       | RA         | Dec.      | Name          | Telescope | Instrument | Exposure | Grating   | R    | Signal-to-noise ratio <sup>a</sup> | Date observed    |
|------------|------------|-----------|---------------|-----------|------------|----------|-----------|------|------------------------------------|------------------|
| 011.8+03.7 | 17:57:39.6 | −16:49:19 | PHR 1757–1649 | SSO/2.3 m | DBS        | 1200     | 600B/600R | 1800 | 15                                 | 2006 May 24      |
| 326.9+08.2 | 15:18:18.2 | −47:38:28 | MPA 1518–4738 | SSO/2.3 m | DBS        | 300      | 300B      | 1200 | –                                  | 2007 February 24 |
| 327.5–02.2 | 16:02:11.2 | −55:43:30 | MPA 1602–5543 | SSO/2.3 m | DBS        | 600      | 1200R     | 600  | 5                                  | 2007 May 06      |
| 328.8–01.1 | 16:03:41.4 | −54:02:04 | PHR 1603–5402 | ESO/1.5 m | B&C        | 1200     | 25        | 800  | –                                  | 2000 July 03     |
| 349.7+04.0 | 17:02:46.1 | −35:09:02 | PPA 1702–3509 | SSO/UKST  | 6dF        | 1200     | 580V      | 1000 | 20                                 | 2004 August 16   |

<sup>a</sup>Signal-to-noise ratio was measured in the continuum at  $\sim 5900$  Å. When no signal-to-noise ratio is indicated, this means that the continuum was not detected.

**Table B1.** Below are FWHM, EW and dereddened intensities of stellar lines in our discovery spectra. The FWHM and EW of C IV  $\lambda\lambda 5801,12$  and C III  $\lambda 5696$  are marked. All other columns are the intensities of the lines, with C IV  $\lambda\lambda 5801,12 = 100$ . (We do not list the absolute C IV line fluxes because our spectra were not absolutely flux calibrated.) Spaces marked ‘–’ were not seen in the spectra. ‘N.O.’ indicates that the designated line lay in a region of the spectrum which was not observed. ‘P’ indicates that the line is present, but the exact value cannot be measured due to the absence of the continuum or C IV  $\lambda\lambda 5801,12$ . ‘S’ indicates a strong line. ‘W’ signifies a weak line. Again, ‘:’ denotes an uncertain value, while ‘::’ indicates a very uncertain value.

| Object name   | C IV $\lambda\lambda 5801,12$<br>FWHM (Å)* | C IV $\lambda\lambda 5801,12$<br>EW (Å) | C III $\lambda 5696$<br>FWHM (Å) | C III $\lambda 5696$<br>EW (Å) | C III<br>$\lambda 5696$ | O VI<br>$\lambda\lambda 3811,34$ | C II<br>$\lambda 4267$ | He II<br>$\lambda 4686$ | O VI<br>$\lambda 5290$ | O V<br>$\lambda 5590$ | O VII<br>$\lambda 5670$ | C II<br>$\lambda 7236$ |
|---------------|--------------------------------------------|-----------------------------------------|----------------------------------|--------------------------------|-------------------------|----------------------------------|------------------------|-------------------------|------------------------|-----------------------|-------------------------|------------------------|
| PHR 1811–3042 | –                                          | –                                       | –                                | –                              | –                       | –                                | –                      | P                       | P                      | –                     | –                       | –                      |
| BMP 1827–1504 | 3                                          | P                                       | –                                | –                              | N.O.                    | N.O.                             | –                      | –                       | N.O.                   | N.O.                  | N.O.                    | –                      |
| MPA 1921+0132 | 42                                         | P                                       | –                                | –                              | –                       | –                                | –                      | –                       | –                      | –                     | –                       | –                      |
| PHR 0723+0036 | 47                                         | 65                                      | –                                | –                              | –                       | –                                | –                      | 68 <sup>a</sup>         | –                      | –                     | –                       | –                      |
| PHR 0654–1045 | 25                                         | 7                                       | 9                                | 4                              | 46                      | –                                | –                      | 450 <sup>a</sup>        | –                      | –                     | –                       | –                      |
| PHR 1001–6152 | 27                                         | 10                                      | –                                | –                              | –                       | –                                | –                      | 1100::                  | 54::                   | –                     | 13::                    | –                      |
| BMP 1209–5553 | –                                          | –                                       | –                                | –                              | –                       | S                                | –                      | S                       | P                      | –                     | –                       | –                      |
| MPA 1243–6428 | –                                          | –                                       | 9                                | P                              | P                       | –                                | –                      | –                       | –                      | –                     | –                       | P                      |
| MPA 1354–6337 | 45                                         | S                                       | –                                | –                              | –                       | –                                | –                      | –                       | –                      | –                     | –                       | –                      |
| MPA 1405–5507 | 22:                                        | 6:                                      | –                                | –                              | –                       | –                                | –                      | 37::                    | –                      | –                     | –                       | –                      |
| PHR 1416–5809 | 27                                         | 98                                      | 19                               | 240                            | 245                     | –                                | –                      | 63 <sup>a</sup>         | –                      | W                     | –                       | 67:                    |
| MPA 1624–5250 | 6,8:                                       | P                                       | –                                | –                              | –                       | –                                | –                      | –                       | –                      | –                     | –                       | –                      |
| MPA 1611–4356 | 40                                         | 600                                     | –                                | –                              | –                       | –                                | –                      | 17 <sup>a</sup>         | –                      | –                     | –                       | –                      |
| MPA 1655–3535 | –                                          | –                                       | 7                                | 11                             | P                       | –                                | –                      | –                       | –                      | –                     | –                       | P                      |
| PHR 1753–3443 | 29                                         | 12                                      | –                                | –                              | –                       | N.O.                             | –                      | 510 <sup>a</sup>        | W:                     | –                     | –                       | –                      |
| PHR 1753–3428 | 38                                         | 16                                      | –                                | –                              | –                       | N.O.                             | W:                     | 330: <sup>a</sup>       | –                      | –                     | –                       | –                      |
| PHR 1752–3330 | –                                          | –                                       | 6                                | 1                              | P                       | –                                | –                      | –                       | –                      | –                     | –                       | P                      |
| PHR 1731–2709 | 60                                         | P                                       | –                                | –                              | –                       | –                                | –                      | –                       | –                      | –                     | –                       | –                      |
| M2–21         | 7,5                                        | P                                       | –                                | –                              | –                       | –                                | P                      | S                       | –                      | –                     | –                       | P <sup>a</sup>         |
| M1–35         | –                                          | W:                                      | –                                | –                              | –                       | –                                | P                      | P                       | –                      | –                     | –                       | P                      |
| M2–39         | 20                                         | 5                                       | –                                | –                              | –                       | N.O.                             | W:                     | 16                      | 14::                   | –                     | –                       | 120                    |
| M2–42         | 25                                         | 5                                       | –                                | –                              | –                       | N.O.                             | –                      | 900                     | –                      | –                     | –                       | –                      |
| A48           | N.O.                                       | N.O.                                    | N.O.                             | N.O.                           | N.O.                    | N.O.                             | –                      | P                       | N.O.                   | N.O.                  | N.O.                    | –                      |
| Wr 17–23      | 50::                                       | 25::                                    | –                                | –                              | –                       | –                                | –                      | W:                      | –                      | –                     | –                       | –                      |
| Pe 2–8        | 12,12                                      | 50::                                    | N.O.                             | N.O.                           | N.O.                    | N.O.                             | N.O.                   | –                       | N.O.                   | N.O.                  | N.O.                    | P <sup>a</sup>         |
| Pe 1–10       | 53                                         | 5                                       | –                                | –                              | –                       | –                                | –                      | 4100 <sup>b</sup>       | W:                     | 17::                  | –                       | –                      |
| Th 3–13       | 23                                         | P                                       | 30                               | P                              | P                       | –                                | –                      | –                       | –                      | –                     | –                       | P                      |
| M3–38         | 4,2                                        | P                                       | N.O.                             | N.O.                           | N.O.                    | N.O.                             | –                      | S                       | N.O.                   | N.O.                  | N.O.                    | P                      |
| M2–16         | 59                                         | 17                                      | –                                | –                              | –                       | N.O.                             | N.O.                   | N.O.                    | W:                     | –                     | –                       | –                      |
| Sa 3–107      | 7,7                                        | 9                                       | –                                | –                              | –                       | N.O.                             | N.O.                   | N.O.                    | –                      | –                     | –                       | 12                     |
| H1–19         | 17                                         | 5                                       | –                                | –                              | –                       | –                                | –                      | 200:                    | –                      | –                     | –                       | 35:                    |
| M2–27         | 26                                         | 15                                      | –                                | –                              | –                       | –                                | 37:                    | 48:                     | –                      | –                     | –                       | 66:                    |

<sup>a</sup>Blended with other stellar and nebular lines.

<sup>b</sup>Significant nebular component.

\* When two numbers are listed, individual components of the doublet were measured.

blend, but we detect a weak N V  $\lambda 4603$  line as well as a very broad  $\lambda 4650$  feature likely due to a blend of N III and C III–IV lines, and broad, bright He II  $\lambda 4686$ , along with the Balmer lines of hydrogen. There is a narrow [O III]  $\lambda 5007$  line which shows there is a surrounding nebula present. Its location makes it a possible outlying member of the Galactic bulge, and it warrants further study.

## APPENDIX B

Table B1 presents FWHM, EW and relative intensities of our discovery [WR] and WELS spectra.

This paper has been typeset from a  $\text{\LaTeX}$  file prepared by the author.