

ON THE ORIGIN AND EVOLUTION OF WOLF-RAYET CENTRAL STARS OF PLANETARY NEBULAE

By

Kyle David DePew

A THESIS SUBMITTED TO MACQUARIE UNIVERSITY
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
DEPARTMENT OF PHYSICS & ASTRONOMY
MARCH 2011



MACQUARIE
UNIVERSITY

FACULTY OF SCIENCE

Except where acknowledged in the customary manner, the material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree in any university.

Kyle David DePew

Acknowledgements

I must first thank my supervisor, Prof Quentin Parker, for recommending me for the MQRES scholarship and taking me on as his student. I have also benefited enormously from the expertise of A/Prof Orsola De Marco, my co-supervisor, who helped me understand the background of Wolf-Rayet central stars. Special thanks also go to Dr David Frew, who, although not an official supervisor, was just as helpful with his seemingly encyclopedic knowledge of planetary nebulae.

I have been supported by a generous Macquarie University Research Excellence Scholarship during my last three and a half years here. This thesis would not have been possible without significant grants of observing time by the Siding Spring and South African Astronomical Observatory time assignment committees. Thanks also go to all the telescope support staff, especially Donna Burton and Geoff White, for help when everything broke down.

I also thank Madusha Gunawardhana, Quentin Parker and David Frew for graciously allowing me access to their paper on SHS flux calibrations prior to publication.

I would also like to thank my fellow PhD students here in the department. I have been extremely fortunate to work among such thoughtful and enjoyable people. Stacey Bright and Niyas Madapatt especially helped me to remember that there was a world beyond the office and served to distract me (sometimes perhaps too much)

from the tedium of my work. I also thank Anna Kovacevic for training me on the 2.3 Metre Siding Spring Telescope, Korinne McDonnell for LaTeX help and general cubicle mateship, as well as the guys from the quantum information group—Johann-Heinrich Schönfeldt, Gerardo Paz Silva, Aharon Brodutch, Ressa Said, Tommaso De Marie, Mauro Cirio, and all the others—for their camaraderie.

Thanks also go to Duane Hamacher, who first put the idea of moving to Australia into my head, a decision which I have not yet had occasion to regret.

I am also grateful to all the professional staff, especially Carol McNaught, for help with all the paperwork.

Finally, I wish to thank my family, my parents Anne and Ron, my sister Alyssa and brother-in-law Aaron, for never once asking me why I've been studying physics for the past decade plus, and for always understanding my desire to see this through to the bitter end.

List of Publications

Papers and Conference Proceedings Produced in the Course of This Thesis

- **DePew K.**, Parker Q.A., Miszalski B., De Marco O., Frew D.J., Acker A., Kovacevic A.V., Sharp R.G., 2011. *Newly Discovered Wolf-Rayet and Weak Emission-Line Central Stars of Planetary Nebulae*. MNRAS, in press.
- Corradi R.L.M., Valentini M., Munari U., Drew J.E., Rodríguez-Flores E.R., Viironen K., Greimel R., Santander-García M., Sabin L., Mampaso A., Parker Q., **DePew K.**, Sale S.E., Unruh Y.C., Vink J.S., Rodríguez-Gil P., Barlow M.J., Lennon D.J., Groot P.J., Giammanco C., Zijlstra A.A., Walton N.A., 2010. *IPHAS and the symbiotic stars. II. New discoveries and a sample of the most common mimics*. A&A, 509, 41.
- **DePew K.**, Frew D.J., Parker Q.A., De Marco O., 2011. *Wolf-Rayet Central Stars of Planetary Nebulae: Their Evolution and Properties*. APN5 Conf. Proceedings, A.A. Zijlstra, F. Lykou, I. McDonald, E. Lagadec, eds., 160.

Abstract

The origin of hydrogen-deficiency in the central stars of planetary nebulae (CSPNe) is currently a topic of heated debate. This class of objects is comprised of Wolf-Rayet ([WR]) stars, weak emission-line stars (WELS), and PG 1159 stars, each differentiated by a set of unique spectral characteristics. For some time, there have been questions surrounding the evolutionary status of these rare stars: what environmental conditions, such as chemical abundances, are necessary for their emergence, whether any of them represent different stages of development in the same class of stars, and what the characteristics of their progenitors may be. However, such investigations have been hampered by a lack of a sufficient number of these stars and their various sub-classes until recently.

This thesis presents the significant discovery of 22 new [WR] stars and 10 new WELS, many uncovered specifically during this thesis in the course of the MASH survey and through serendipitous fibre placement during follow-up of MASH objects. All examples have been carefully classified as accurately as possible using the best current available data though for many this remains a preliminary assignment pending deeper spectra. This work expands the known sample of H-deficient stars by 30%, allowing a more detailed study of their properties than previously possible and moving us closer to a more complete census of local H-deficient CSPNe.

In the course of our classifications, Abell 48 was found to be a particularly interesting object. Further analysis of nebular chemical abundances, modeled temperature, and ionization state as indicated by the chemical species present suggests that the CSPN of Abell 48 may be very similar to the CSPN of PB 8, which has recently been redesignated as the founding member of a new and rare [WN/WC] class (Todt et al. 2010). Its similarity to and differences with other oxygen-rich [WO] and carbon-rich [WC] stars as well as previously identified [WN] stars are examined.

All these stars have also been studied in the context of a new subclass-dynamical age relationship that we have also discovered. This major finding is the first to show evidence of an evolutionary trend amongst the [WR] population and was made possible by use of the powerful new surface brightness-radius (SB-r) relation of Frew (2008) that can, at last, provide accurate distances to PN (and hence also their central stars). Key data acquired here as well as modeled effective temperatures and excitation classes of other [WR]s, WELS and PG 1159 central stars found in the literature were also utilized in generating this relationship.

Finally, continuing with the SB-r relation, the scale heights of the most complete available sample of [WR], WELS and PG 1159 CS populations are determined and compared. These data show that both WELS and PG 1159 stars are found to possess significantly higher Galactic heights than the members of the [WR] class, implying that PG 1159s do not all descend from [WR]s, and that WELS are not evolutionarily related to [WR]s. This is another major finding of this work. It is possible, however, that the WELS class, and perhaps the PG 1159 class as well, are heterogeneous groups.

Contents

Acknowledgements	v
List of Publications	vii
Abstract	ix
List of Figures	xvii
List of Tables	xxix
1 Introduction	1
1.1 Life Cycle of Low- to Intermediate-Mass Stars	2
1.1.1 Introduction to the Hertzsprung-Russell Diagram	3
1.1.2 Description of the Life Cycle of Low- to Intermediate-Mass Stars	3
1.1.3 Description of PNe	6
1.2 Past PNe Surveys	9
1.3 Central stars of PNe	11
1.4 General Spectral Classifications of Massive Wolf-Rayet Stars	12
1.4.1 General Properties of Massive Wolf-Rayet Stars	15
1.4.2 Theorized Evolution of Massive Wolf-Rayet Stars	16

1.5	Wolf-Rayet Central Stars of PNe and their classification	22
1.6	Taxonomy of Hydrogen-Deficient Central Stars of PNe	25
1.6.1	Theorized Evolution of Wolf-Rayet Central Stars of PNe and Thermal Pulse Scenarios	27
1.6.2	The Born Again Scenario	30
1.6.3	PG 1159 and WELS Stars	31
1.6.4	Modeling of [WR] Stars	35
1.7	Conclusion	36
2	Data Reduction	37
2.1	The Dual Beam Spectrograph	38
2.2	Basic Spectroscopic Data Required	39
2.2.1	Bias Frames	40
2.2.2	Dark Frames	41
2.2.3	Flat-Field Frames	41
2.2.4	Sky Flats	41
2.2.5	Calibration Frames	42
2.2.6	Target frames	42
2.2.7	Cosmic Rays	42
2.2.8	Spectrophotometric Standard Stars	42
2.3	Spectroscopic Data Acquired During This Thesis	43
2.4	The Image Reduction and Analysis Facility; IRAF	43
2.4.1	Reduction of DBS Data	44
2.4.2	Flat Preparation	45
2.4.3	Flat Subtraction	47
2.4.4	Cosmic Ray Cleaning	48
2.4.5	Spectrum Extraction	48
2.4.6	Wavelength Calibration	50

2.4.7	Flux Calibration	51
2.5	WiFeS Data	52
2.5.1	File Preparation	53
2.5.2	Calibrations	54
2.5.3	Final Reduction	55
2.6	SPIRAL Data Reduction	55
2.6.1	Data Preparation	56
2.6.2	Data Reduction	60
3	New and Old Hydrogen-Deficient Objects	63
3.1	Introduction	64
3.1.1	[WR]s in the MASH Sample	67
3.2	Spectroscopic Observations	68
3.3	Classification Schemes	71
3.4	Individual Objects	72
3.4.1	New [WR] Stars	75
3.4.2	Possible [WR]s and WELS	84
3.5	Conclusions	89
3.6	Comprehensive Table of Hydrogen-Deficient Central Stars of Planetary Nebulae	89
4	Abell 48 and the [WN/WC] Class	105
4.1	Introduction	106
4.2	Massive WR stars and the WN Class	107
4.3	The Putative [WN] Class	107
4.3.1	PM5	108
4.3.2	LMC-N66	109
4.3.3	PB8	112

4.3.4	Considerations for [WN] Stars	112
4.4	Spectroscopic Observations	114
4.5	Flux Measurements and Distance Calculation	115
4.6	Reddening	116
4.6.1	Abell 48: Planetary Nebula or Massive Ring Nebula?	117
4.7	The Abell 48 Nebula–Spectral Characteristics and Other Properties	119
4.8	The Central Star	121
4.8.1	Central Star Properties	124
4.9	Nebular Plasma Diagnostics and Line Ratios	127
4.9.1	Electron Temperature	129
4.9.2	Electron Density	129
4.9.3	Finding Plasma Diagnostics and Abundances Using HOPPLA	130
4.10	Calculating the Ionized Mass	136
4.11	Comparison with PB 8	138
4.12	Evolutionary Considerations	139
4.12.1	The AGB Final Thermal Pulse	141
4.12.2	The Late Thermal Pulse	141
4.12.3	The Very Late Thermal Pulse	142
4.12.4	Which Pathway for Abell 48?	142
4.13	Conclusions	143
5	New Evolutionary Relationships for Wolf-Rayet Central Stars of Planetary Nebulae	147
5.1	Introduction	148
5.2	The H α Surface Brightness-Radius Relationship	149
5.3	Determination of Planetary Nebula Dynamical Age	155
5.4	The [WR] Dynamical Age Sequence	156
5.5	Excitation Classes and Effective Temperatures	157

5.5.1	Constructing an Excitation Class- [WR] Subclass Function . . .	160
5.6	H α Surface Brightness Evolution	163
5.7	Discussion & Conclusions	168
6	A Comparison of the Galactic [WR], WELS and PG 1159 CSPN Populations	171
6.1	Introduction	172
6.2	Data Collection and Analysis	173
6.3	Galactic Distributions	173
6.3.1	Considerations Involving White Dwarfs	187
6.4	Evolutionary Scenarios	189
6.5	Conclusions	190
7	Conclusions	199
7.1	The [WR] Population	200
7.2	The [WN/WC] Stars	200
7.3	The Subclass Evolutionary Sequence	202
7.4	The Evolutionary Relationship Between [WR]s, WELS and PG1159 Stars	202
7.5	Future Work	203
	References	205

List of Figures

1.1	An example of a Hertzsprung-Russell diagram showing the evolution of a $2 M_{\odot}$ star of solar metallicity. Note the main sequence line in the right lower quadrant. The blue line represents a born-again track, triggered by a very late thermal pulse (see §1.6.2). The red star represents PG 1159-035, an H-deficient star, and the green star represents NGC 6853, an H-normal star. Numerical labels indicate the logarithm of the approximate time in years for the indicated evolutionary phase. Taken from Herwig (2005).	4
1.2	A diagram of the layers of an AGB star. During the AGB phase, a star will begin thermal pulsations. Convection currents will form in the convective zone, eventually throwing core matter into the surrounding space and enriching it with nucleosynthetic elements. Adapted from Karakas et al. (2002).	5
1.3	The Wolf-Rayet spectral classifications of van der Hucht (2001). This system was developed for use with massive Wolf-Rayets.	13
1.4	The WR classification system of Crowther et al. (1998). This system was developed for both massive and CSPN types of Wolf-Rayets.	14

-
- 1.5 An example of a Wolf-Rayet spectrum, from star WR1, the first Wolf-Rayet star identified. Note the strong emission lines. Retrieved from <http://www.amateurspectroscopy.com/Astrophysics-spectrum.htm> on 6 March 2008. 16
- 1.6 Spectra of several [WR] stars, taken from Parker & Morgan (2003). . . 24
- 1.7 This figure, from Acker & Neiner (2003), shows the drastic difference in linewidth between several [WO4]pec stars and a WELS star. The thick line gives the spectrum for M 1-51, the thin solid line Cn 1-5, M 1-32 the dashed line, and PM 1-89 the dashed-dotted line. The dotted line shows the spectrum of M 1-61, a WELS star, for contrast. 32
- 2.1 A picture of the DBS, mounted on the 2.3 Metre telescope. The blue arm is to the left and the red is to the right. 39
- 2.2 Example frames taken on the 2.3m in May 2008. At top is a bias frame. The noisy nature is apparent. The middle frame is a flat-field taken with a quartz lamp. The illumination is smooth, as the lamp emits a continuum of wavelengths. This is in contrast to the example arc lamp exposure at bottom, which clearly shows the distinct wavelengths produced in the gas. 40
- 2.3 A simplified flow chart illustrating the basic data reduction process. As illustrated, dark frames (if necessary) are subtracted from a target frame, while the bias signal of the chip is subtracted off of the flat-field image. The quotient of the remaining science image and the perfect flat is taken to produce the output image, which will then be wavelength- and flux-calibrated. 45

2.4	An image of the CCD chip after observing the planetary nebula Abell 48 through the blue arm of the 2.3 Metre Dual Beam Spectrograph. The spatial direction (the direction of the slit) is along the vertical axis, and the dispersion direction is along the horizontal axis. This observation was taken 11 May 2008.	47
2.5	An image of the CCD chip after observing the planetary nebula Abell 48 through the red arm of the 2.3 Metre Dual Beam Spectrograph (DBS). As before, the spatial direction is along the vertical axis, and the dispersion direction is along the horizontal axis. This exposure was taken concurrently with the blue image on 11 May 2008.	47
2.6	The previously presented spectrum after cosmic ray cleaning.	49
2.7	A screenshot of PNDR. The horizontal lines represent the upper and lower bounds of regions on the plate which the user wishes to be binned. Separate regions are designated for sky (background) lines, for upper and lower nebular regions (either side of the star), and the star itself.	50
2.8	An example of a nebular spectrum awaiting wavelength- and flux-calibration.	51
2.9	The selection of gratings available on WiFeS. Taken from the the Australian National University WiFeS user pages (http://msowww.anu.edu.au/observing/ssowiki/index.php/WiFeS_Main_Page).	53
2.10	The image slicer of WiFeS, as shown in the observing manual, available at http://msowww.anu.edu.au/observing/ssowiki/index.php/WiFeS_Main_Page . Note the concentric design, which follows the same concepts as McGregor et al. (1999) and McGregor et al. (2003).	53
2.11	An image of the PN PB8 in H α after subtracting sky lines.	55
2.12	The AAOmega spectrograph.	56
2.13	A schematic diagram of AAOmega, showing the red camera in high dispersion mode, and the blue camera in low dispersion mode.	57

2.14	The SPIRAL IFU, which is designed for use with AAOmega. Its 32×16 array of fibres allows a possible 512 separate spectra.	57
2.15	At left is a composite colour image of the MASH PN PHR1811-3042 (see Chapter 3) with $H\alpha$, short red and B band images represented as red, green and blue respectively, obtained from the online SuperCOSMOS survey data (Parker et al. 2005). At right is the same PN observed by SPIRAL at commissioning on 28 June 2006. Images taken from Sharp & The Aaomega+Spiral Team (2006a).	58
2.16	The 2dfdr data reduction facility interface.	59
3.1	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.	73
3.2	A montage of the non-MASH PNe found to contain a true or candidate [WR] or WELS central star. As in Fig. 3.4, each $H\alpha/SR/B_J$ composite colour image (Parker et al. 2005; Hambly et al. 2001) 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.	74
3.3	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).	90

3.4	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).	91
3.5	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).	92
3.6	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).	93
4.1	The spectrum of LMC-N66 as observed in 1995 and 1996, as presented in Peña et al. (1997a). The upper two cover the UV and blue range, and the bottom two expand the spectral regions around the He II, C IV and N V lines to show the substructure evident in these features.	110
4.2	The best fitting model of PB 8's spectrum, adapted from Todt et al. (2010).	113
4.3	A montage of all currently known [WN] and [WN/WC] objects. Clockwise from top left are Abell 48, PB8, LMC-N66, and PM5. Abell 48, PB8 and PM5 are shown in $H\alpha$ /SR/ B_J false-colour composites where $H\alpha$ is represented by red, SR by green, and B_J by blue (Parker et al. 2005). All apart from LMC-N66 are $60'' \times 60''$. $5'' \times 5''$ HST STIS image of LMC-N66, taken from Peña et al. (2004), was observed through the MIRVIS grating. Note the bipolar appearance of LMC-N66 and PB8 compared to the spherical and elliptical appearances of PM5 and Abell 48, respectively, showing that there do not appear to be any common morphological traits in the surrounding nebulae.	118

4.4	The spectrum of PM 5, as presented in Morgan et al. (2003). Note the 7118Å feature, which may be mistaken for a broad C II line, but derives instead from a series of N IV lines.	119
4.5	The SHASSA image of Abell 48. The coarse resolution (48" pixels) reduces this PN to four pixels, designated by the concentric circles. . .	120
4.6	Three images of Abell 48. At left, a false-colour image of Abell 48 in the J, H and K bands from 2MASS (Skrutskie et al. 2006). J, H and K wavelengths are represented as blue, green and red respectively. Image dimensions are 3" × 3". The faint purple extended ring of emission is expected from a true PN (Cohen et al. 2010). At middle is a composite H α /SR/B $_J$ colour image (Parker et al. 2005), and at right is a radio image of Abell 48 from NVSS (Condon & Kaplan 1998). Dimensions in the middle and right panels are 90" × 90".	121
4.7	The blue nebular spectra of Abell 48 and PB 8 for comparison, obtained from WiFeS, with the three important nebular lines—H β λ 4861 and [O III] $\lambda\lambda$ 4959,5007 labelled.	122
4.8	The red nebular spectra of Abell 48 and PB 8 for comparison, obtained from WiFeS, with labelled nebular lines at [O I] λ 6300, [N II] $\lambda\lambda$ 6548,84, H α λ 6563 and [S II] $\lambda\lambda$ 6717,31.	123
4.9	A close-up view of the [S II] lines at 6717 and 6731Å, normally used for plasma diagnostics.	124
4.10	The blue spectrum of the central star of Abell 48, taken by Wachter et al. on 4 Sep 2008 with the 200" Hale Telescope at Palomar Observatory. The spectral resolution is approximately 5-7 Å. Note the presence of N V $\lambda\lambda$ 4604,4620 and the prominent He II λ 4686 feature.	127

-
- 4.11 The red spectrum of the central star of Abell 48. Again, this spectrum was taken by Wachter et al. on 4 Sep 2008 with the 200" Hale Telescope at Palomar Observatory. The spectral resolution is approximately 5-7 Å. Note the He II λ 5412 line and the N IV λ 7116 feature, which can be mistaken for a C II λ 7118 line. 128
- 4.12 The dereddened spectral energy distribution of the central star of Abell 48, reconstructed from photometric measurements from the available literature sources. The points represent the dereddened fluxes of the central star. Massive WN overlays have been divided by constant factors to match the magnitude in V in order to compare slopes. Note the very close fit by the 50.1 kK model. Massive WN models courtesy of Jim Herald. 134
- 4.13 An H α image divided by the broad-band 'SR' quotient image of Abell 48, created using SHS data. There appear to be two sets of faint arcs that might be associated with previous ejecta from the host star that are identified here for the first time. To the northwest there appear to be two faint closely spaced arcs about 30 arcseconds in extent, with the outermost being 46 arcseconds from the CSPN. To the south there appears to be another faint shorter arc some 105 arcseconds from the CSPN. These could be evidence for opposing jets ejected prior to the main nebular shell, as seen in other PNe such as NGC 3918. The different observed angular distances of the northern and southern arcs from the CSPN could be the result of their projection onto the plane of the sky rather than anything dynamical. 140

4.14	A $5'' \times 5''$ $H\alpha$ image divided by broad-band 'SR' quotient image of PB8 created using SHS data. There is a faint outer asymmetric shell outside of the inner nebula (centered on the host star) that is clearly associated. Again this represents previous ejecta from the host star that has been identified here for the first time. The northeast section of the shell is $38''$ from the CSPN and the southwest component $27''$ from the CSPN. The fact that the only two known [WN/WC] CSs reside in PNe that possess faint outer haloes may be significant if it reflects some ejection mechanism related to the star's chemistry.	145
5.1	The surface brightness-log radius (SB-r) relation, based on a sample of 122 calibrating PNe. The line is a least-squares bisector fit (Isobe et al. 1990). Taken from Frew (2008).	151
5.2	A comparison of high-excitation (HE) and common-envelope PNe together versus others, illustrating the systematically lower $H\alpha$ surface brightnesses in the former group. Taken from Frew (2008).	152
5.3	The subclass-dynamical age relationship. Subclass index indicates: [WO1]=1, . . . , [WO4]=4, [WC4]=5, . . . , [WC11]=12. WELS are represented by subclass index 13 and PG1159 stars are represented at number 0. PB 8 has been placed at subclass index 6.5, consistent with its former classification of [WC5-6] (Acker & Neiner 2003). Note the apparent quick evolution from [WC9] to [WC5].	157
5.4	The subclass-excitation class relationship, using the ρ EC method of Reid & Parker (2010). As above, subclass index indicates: [WO1]=1, . . . , [WO4]=4, [WC4]=5, . . . , [WC11]=12. A distinct general trend is clearly evident with the hottest CSPN inferred from the high excitation class values correlating with the early [WO] subclass.	161

5.5	The subclass-effective temperature relationship. 'X's represent [WR]s, stars the WELS, squares the [WC]-PG1159s, and triangles the [WN/WC] stars PB 8 and Abell 48. The WELS denoted by half-filled pentagons represent upper limits for the central stars of NGC 6543 and NGC 6629. Temperature sources are noted in Table 5.3.	166
5.6	H α surface brightness versus spectral type of H-deficient CSPNe.	167
6.1	The Galactic distribution of the [WR], WELS and PG 1159 stars in our sample. The figure is oriented such that an observer looking toward the centre of the Galaxy finds objects with small positive longitudinal values on the left, positive Galactic latitude direction up, etc.	175
6.2	A histogram showing the distribution of [WR]s as a function of Galactic height $ z $. The black line corresponds to the exponential fit function.	176
6.3	A histogram showing the distribution of WELS as a function of Galactic height $ z $	176
6.4	A histogram showing the distribution of PG 1159 central stars as a function of Galactic height $ z $	177
6.5	The distribution of [WR], WELS and PG 1159 stars with derived distances smaller than 3 kpc, where the significant differences between the [WR], WELS and PG 1159 Galactic height distributions can be seen more clearly.	182
6.6	A histogram showing the distribution of a volume-limited sample of [WR] central stars as a function of Galactic height $ z $. Here all included [WR]s are within 3 kpc. Note that 26 of the 28 [WR]s in this sample have $ z $ heights below 300 pc.	183
6.7	A histogram showing the distribution of a volume-limited sample of WELS central stars as a function of Galactic height $ z $. Here all WELS within 3 kpc are included in the plot.	184

-
- 6.8 The changing spectrum of Longmore 4, as presented in Werner et al. (1992). Note the sudden appearance and gradual decline of emission lines C IV $\lambda 4658$ and He II $\lambda 4686$, to the point where they form an absorption trough in the last spectrum, consistent with a PG 1159 star. C IV $\lambda \lambda 5801, 12$, O IV $\lambda \lambda 5279, 5289$ and He II $\lambda 6560$ also briefly appear before declining in strength. 186
- 6.9 A plot of calculated PG 1159 PN radii versus effective temperatures. There does not seem to be a relationship between the two variables. . . 187
- 6.10 One possible evolution scenario for the evolution of [WR]s, in which the [WCL]s evolve into [WCE]s, [WO]s, down through the PG 1159 stages and into the white dwarf region of the H-R diagram. Boxes are overlaid on top of the H-R diagram of Herwig (2005). 190
- 6.11 A second possible evolution scenario for the evolution of [WR]s, in which the [WCL]s evolve into WELS before becoming [WCE]s. This possibility is considered because WELS effective temperatures and $H\alpha$ surface brightnesses fall between those of [WCL]s and [WCE]s. This scenario is however unlikely because of the difference in Galactic heights between these populations. 191
- 6.12 A third possible evolution scenario for the evolution of [WR]s, in which the PG 1159 class is a common endpoint for both [WR] and H-deficient WELS evolution. 192
- 6.13 A possible evolution scenario for the evolution of WELS, in which the H-rich types evolve into hybrid PG 1159 and then DAO and DA white dwarfs. 193
- 6.14 The typical evolution sequence for aging H-rich central stars, for comparison. 194

6.15	The spectrum of the binary central star V477 Lyrae, presented in Pol- lacco & Bell (1994). Note the N III-C III-C IV $\lambda 4650$ complex.	196
6.16	Two WELS spectra from Marcolino & de Araújo (2003). Note the sim- ilarity of the N III-C III-C IV $\lambda 4650$ complex to that seen in Figure 6.15.	197

List of Tables

2.1	A summary of observing runs carried out in the course of this thesis. Spectral resolution and wavelength coverage varied according to the specific gratings used on the night. Please refer to later chapters for details on these values.	44
3.1	Observational details of the new CSPNe discovery spectra.	70
3.2	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.	88
3.3	All known Galactic PNe with [WR], WELS and PG1159 central stars. .	94
3.4	All known Galactic PNe with [WR], WELS and PG1159 central stars. .	95
3.5	All known Galactic PNe with [WR], WELS and PG1159 central stars. .	96
3.6	All known Galactic PNe with [WR], WELS and PG1159 central stars. .	97
3.7	All known Galactic PNe with [WR], WELS and PG1159 central stars. .	98
3.8	All known Galactic PNe with [WR], WELS and PG1159 central stars. .	99
3.9	Observation details of the objects listed in Appendix A.	102

3.10	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.	104
4.1	Properties of the [WN/WC] Stars	113
4.2	Observation details for Abell 48. All observations were taken at Siding Spring Observatory, on the 2.3 metre telescope, using the Wide Field Spectrograph (WiFeS).	114
4.3	An abbreviated comparison of quantities for Abell 48 if it is a PN versus a ring nebula.	118
4.4	Nebular lines found in Abell 48, taken from the 2.3 metre April 2010 spectrum. $\lambda_{Helio}(\text{\AA})$ signifies the wavelength after heliocentric correction. The flux of H β is in 10^{-15} erg/cm ² /s/ \AA , but the remainder are set such that H β =100.	132
4.5	Stellar lines found in the CSPN of Abell 48, taken from the spectra of Wachter et al. (2010) and our own WiFeS data. λ_{Helio} represents the heliocentric velocity corrected wavelength of the line, while λ_{Sys} signifies the wavelength after systemic velocity correction. λ_{Lab} denotes the laboratory measured value.	133
4.6	Photometric values of the central stars of Abell 48 and PB 8.	135

4.7	Nebular chemical abundances, obtained from HOPPLA. Here $\log(H) = 12$. Line ratios for the PB 8 analysis were taken from Girard et al. (2007). Abundances for Abell 48 are only lower limits (see §4.11).	138
4.8	Properties of the central stars of Abell 48 and PB 8. Values for PB 8 have been taken from Todt et al. (2010).	139
5.1	Wolf-Rayet, WELS and PG 1159 central stars used for the subclass-dynamical age relation.	158
5.2	Wolf-Rayet central stars used for the subclass-excitation class relation, with relative intensities and excitation classes.	162
5.3	Wolf-Rayet central stars used for the subclass-temperature relation.	164
5.4	H-deficient central stars used for the subclass- $H\alpha$ surface brightness relation.	165
5.5	H-deficient central stars used for the subclass- $H\alpha$ surface brightness relation (continued).	167
6.1	The numbers of known [WR], WELS and PG 1159 star CSPNe, before and after MASH, as well as the number that are known to be within 3 kpc, and the average Galactic height $ z $ and scale heights. It must be noted that the number within 3 kpc is merely a lower limit.	173
6.2	Galactic Distribution of Objects	178
6.3	Galactic Distribution of Objects	179
6.4	Galactic Distribution of Objects	180

