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A Method for the Direct Determination of the Wind Electron Temperature of WC10 Central Stars of Planetary Nebulae

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Abstract. We present the results of an analysis of the winds of WC10 central stars of planetary nebulae, CPD–56°8032 and He 2–113 for which AAT/UCLES data were obtained. Our analysis uses the fluxes in individual C II auto-ionising multiplet components to obtain the wind electron temperature of the C^{2+} emitting region for CPD–56°8032 (T_e=18 500 K) and He 2–113 (T_e= 13 600 K).

1. Introduction

Low and intermediate mass stars (M~1–8 $M_\odot$) enter the Asymptotic Giant Branch after core helium exhaustion, during which alternate shell-burning of hydrogen (~90% of the time) and of helium (~10%) occurs, the latter following a helium shell flash. The He shell-flash may provide the mechanism responsible for removing mass from the star and eventually triggering the ejection of the entire outer envelope. If this ejection completes just before a helium pulse, the resulting central star should be H-poor, while if it completes during quiescent H-burning it should be H-rich. Amongst the H-deficient central stars of planetary nebulae (CSPN), a significant fraction (~15%) show a WC Wolf-Rayet emission line spectrum, characteristic of a strong, dense stellar wind, despite having had quite different evolutionary histories to the massive (M~50 $M_\odot$) classical carbon sequence (WC) Wolf-Rayet stars. For these stars, the same WC classification criteria can be applied. While classical WC stars belong to excitation classes WC4–9, WC central stars occupy either very high (WC1–4) or low (WC8–11) excitation classes (Tylenda *et al.* 1993). The observed gap between early (WCE) and late (WCL) CSPN may indicate a rapid evolution within this domain.

Amongst the [WCL] stars CPD–56° 8032 (see Fig. 1) has been classified as both WC10 and WC11, but we argue that WC10 is the appropriate classification for this star. Our argument is based on the fact that CPD–56° 8032 was put into the WC11 class by the classification of SwSt1 (HD167362) as the sole representative of the WC10 class. However if the spectrum of SwSt1 is compared with that of CPD–56° 8032 or any WC 11, 9 or 8 star, it is clear that SwSt1 does not belong to the WC class and might be better classified as a weak emission line star (Tylenda *et al.* 1993).

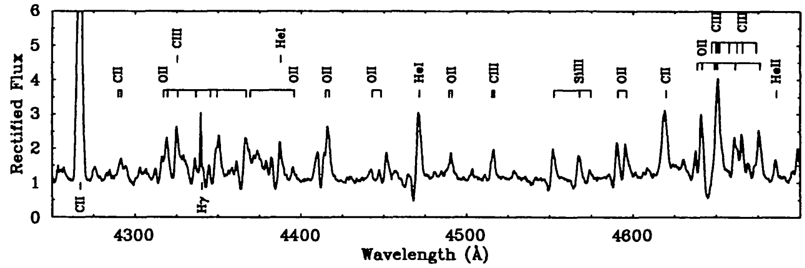

Figure 1. A section of the AAT/UCLES spectrum of CPD–56° 8032

2. Dielectronic line analysis.

A great number of lines in the spectra of WC CSPNe are recombination lines. Of these, some are due to the process of low temperature dielectronic recombination (Nussbaumer & Storey 1984) and originate from quasi-bound states at energies just above the ionisation limit of the ion in question. Such states are formed by the collision of an electron with the ion and may decay to other bound or quasi-bound states with the emission of radiation, or to a true continuum state yielding an ion and a free electron with no emission of radiation (autoionisation).

The rate of autoionisation is usually considerably larger than that for radiative decay and consequently the population of the autoionising state is close to that given by the Saha equation in terms of the electron and ion populations and the electron temperature. In general we may relate the actual population density N_u to that given by the Saha population for the same state *via* a departure coefficient b_u by,

$$\left(\frac{N_u}{N_e N_+}\right) = \left(\frac{N_u}{N_e N_+}\right)_{Saha} b_u,$$

where $b_u = \Gamma_u^A \,/\, (\Gamma_u^A + \Gamma_u^R)$ is close to unity. Here, Γ_u^A is the autoionisation probability of the state and Γ_u^R is the total probability of radiative decay to all lower levels. The emissivity in a particular transition is then given by $\epsilon = N_u \Gamma_{ul}^R \, h \, \nu_{ul}$, where Γ_{ul}^R is the radiative probability for the transition in question.

The emissivity in such a transition depends on the electron temperature through the factor $\exp(-E/kT_e)$ in the Saha equation, where E is the energy of the upper state relative to the ionisation threshold. If we compare two lines originating from different upper states we can in principle, infer the electron temperature. This, provided that the atomic data necessary to evaluate the departure coefficient b_u is available, that the lines are emitted from the same physical volume and that the wind is optically thin to them.

We have extended the earlier calculations of Barlow & Storey (1992) to obtain the required radiative and autoionisation probabilities in intermediate coupling. In the case of autoionisation, we have combined the accurate LS-coupled decay rates of Davey (1995) with transformation coefficients obtained from the general purpose atomic structure code SUPERSTRUCTURE (Eissner *et al.*, 1974, Nussbaumer & Storey, 1978). These calculations show that in the case of C II, the autoionisation probabilities, although larger than the corresponding radiative decay probabilities, are not large enough to cause major broadening of the resulting spectral lines. Observational confirmation of this fact is given below.

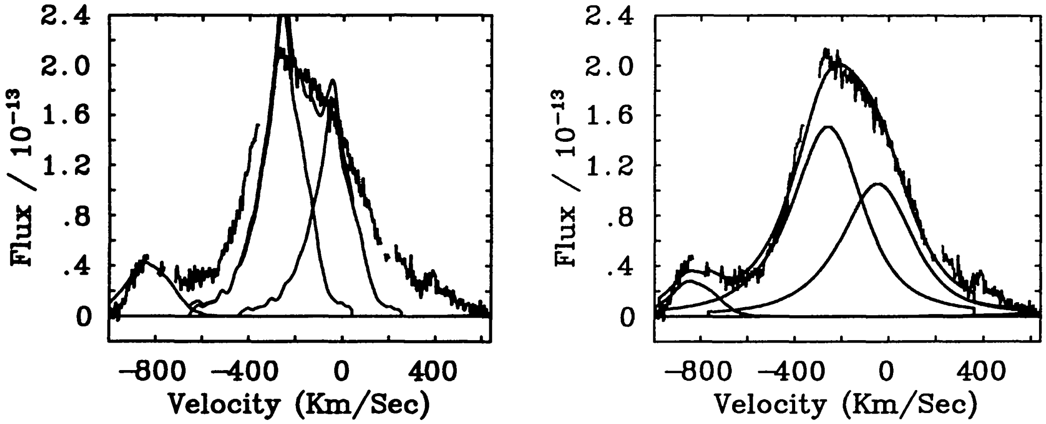

Figure 2. Fits to four spectral regions of CPD–56° 8032 containing dielectronic (solid profiles) and other recombination lines (dotted profiles)

We have identified four such lines in an AAT/UCLES spectrum of CPD–56° 8032 at wavelengths of 4620 Å, 4963 Å, 5115 Å and 8800 Å. We make multi-component least-squares fits to the spectral regions around these lines, including any other carbon and oxygen lines that may be present. The fits are carried out in velocity space using the profile of the 4802 Å 4f–8g transition as a template and the results are shown in Fig. 2. The profiles of the lines in the 4f-ng series become narrower as n increases, due to decreasing optical thickness (Hillier 1989), with lines with $n \geq 8$ apparently being optically thin. With the exception of λ8800 (for which more details are provided later in the text), the dielectronic lines cannot be satisfactorily fitted with any profile broader than that of λ4802, and we conclude that these lines are also optically thin, as one might expect from the high energies of the initial and final states.

Table 1. Atomic data for the calculation of auto-ionising spectral line profiles. Probabilities are in s^{-1}, wavelengths in Å

Transition	λ	Γ_u^A	Γ_u^R	Γ_{ul}^R
3d′ ($^2F^o_{7/2}$) - 3p′ ($^2D_{5/2}$)	8793.8	1.49× 10^{12}	2.48× 10^9	1.99× 10^7
3d′ ($^2P^o_{3/2}$) - 3p′ ($^2P_{3/2}$)	4964.7	1.90× 10^{11}	2.00× 10^9	2.89× 10^7
4f′ ($^2G_{9/2}$) - 3d′ ($^2F^o_{7/2}$)	4619.2	1.63× 10^9	2.56× 10^8	1.84× 10^8
4f′ ($^2D_{5/2}$) - 3d′ ($^2P^o_{3/2}$)	5113.7	8.26× 10^{10}	2.10× 10^8	6.94× 10^7

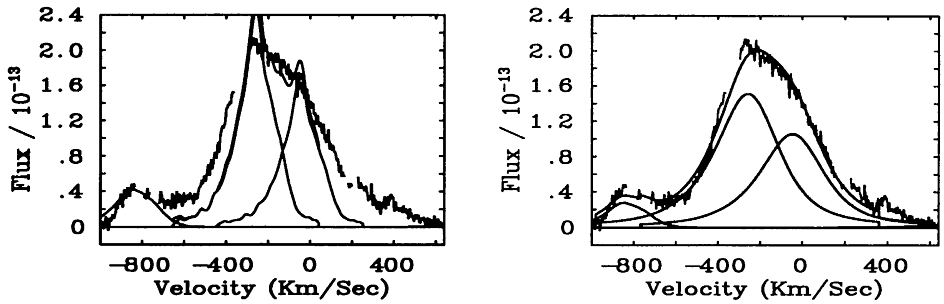

Figure 3. Comparison between fits to the 8800 Å lines before (left panel) and after (right panel) convolving the prototype λ4802 profile with a Lorentzian of width corresponding to the lifetime of the state

Table 1 shows that the greatest autoionisation broadening should occur for λ8800, for which $\Gamma_u^A = 1.49 \times 10^{12}$ s^{-1} corresponds to a FWHM of 210 km s^{-1}. Fig. 3 shows two fits to this transition. In the left frame, the fit was carried out using the λ4802 profile described above. In the right frame, this profile was convolved with a Lorentzian whose width corresponds to the calculated auotoionisation lifetime of the upper state. The agreement with observation is excellent. We also note that the autoionisation probabilities listed in Table 1 are relatively low because the underlying core transition (2s2p(^{3}P^o) – 2s^2(^{1}S)) is not optically allowed.

We have determined the wind electron temperature, T_e, by simultaneously minimising the difference between the measured fluxes and the predicted emissivities for all four lines, and obtained T_e=18 500 K ± 1500 K for the C^{2+} emitting region of CPD–56° 8032.

The same analysis was performed on AAT/UCLES observations of the WC10 star He 2–113 and the wind electron temperature derived to be 13 600 K ± 800 K. An independent prediction for the wind electron temperature of CPD–56° 8032 (T_e=20 000 ± 1500 K) was obtained by Crowther *et al.* (1995) using atmosphere modelling code of Hillier (1990). The closeness of the two results gives strength to the dielectronic line analysis argument.

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