Astron. Astrophys. 234, 410–418 (1990)

ASTRONOMY
AND
ASTROPHYSICS

The UV spectrum of the WC 11 star CPD $-56°8032$

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Received August 16, accepted November 9, 1989

Abstract. UV observations of the WC 11 central star of the compact planetary nebula CPD $-56°8032$ show that the continuum flux is variable. This variability appears to be caused by a change in the circumstellar extinction properties. The UV energy distribution can be fitted with helium star models with $T_{\rm eff} \sim 25000$ K, after correcting for two types of reddening (1) $E_{B-V} \sim 0.4$ using Seaton's reddening curve applicable to diffuse interstellar medium (2) $E_{B-V} \sim 0.25$ to 0.30 using the reddening curve defined by the laboratory extinction properties of amorphous carbon grains of Bussolletti et al. The stellar wind mass loss is estimated from the P-Cygni profile of C II λ 1760.6 from the high resolutions IUE spectrum. Similarities with other WC 11 stars are discussed.

Key words: stars: mass loss – Wolf Rayet stars – planetary nebulae – CPD $-56°8032$

1. Introduction

Webster and Glass (1974) have identified a group of four cool Wolf-Rayet central stars of planetary nebulae which show large infrared excesses. These are CPD $-56°8032$, He 2-113, M 4-18 and V 348 Sgr, which form an extension of the carbon sequence in Wolf-Rayet stars to WC 11. One of these stars, V 348 Sgr, is classified as a hot RCrB type variable. Thus this group might form a link between the planetary nebulae and RCrB type stars. The brightest member of this group is CPD $-56°8032$. The optical spectrum of this star shows strong emission lines due to C II, C III, He I, O II etc., in addition to the nebular lines of [O II], [O I], [S II], [N II], [S III], (Cowley and Hiltner, 1969; Thackeray, 1977; Rao, 1987). The star seems to be surrounded by an optical nebulosity of 1.″3 diameter (Roche et al., 1986). The nebular properties have recently been studied by Rao (1987). The central star is known to be hydrogen deficient and the H II emission lines seen in the optical spectrum are due to a nebulosity (Aitken et al., 1980; Rao and Houziaux, 1989). The star not only is a strong IRAS source but also shows an optically thin free-free spectrum between 2.7 to 14.7 GHz (Purton et al., 1981).

The study of the UV spectrum by Houziaux and Heck (1982) (hereafter HH) obtained with IUE brought out several interesting aspects regarding both the line spectrum and the nature of the circumstellar dust.

1.1. *The UV line spectrum*

The carbon abundance for the nebula estimated from C III] λ 1908 and C II] λ 2326 is very high ($\log C \sim 9.39$), even higher than that for extreme carbon-enriched PN Hf 2-2 (Kaler, 1988). At the same time, HH report the presence of a feature at λ 1751 of N III] in comparable strength to λ 1908 of C III] which would also imply a high nitrogen abundance. Such a high nitrogen abundance is not supported by the analysis of the optical nebular lines (Rao, 1987). HH also identified the presence of the He II line in the UV spectrum which implies a very hot central star. However, even in the optical spectrum, λ 4686 of He II is only a weak emission and He II λ 1640 does not appear at all. Moreover, the wavelength of these lines correspond to the strong C II transitions.

1.2. *UV reddening*

Another feature which emerged out of the study of HH is the anomalous reddening properties of the circumstellar dust. The interstellar reddening in CPD $-56°8032$, as estimated by Aitken et al. (1980) from both Hα/Hβ measurements as well as the radio - Hβ flux relationship, is $E_{B-V} = 0.6$ and $A_v = 1.83$. Aitken et al. (1980) also estimated the stellar temperature from the Hβ flux employing the Zanstra temperature method of Morton (1969), as 26000 K. The observed UV flux distribution of HH when corrected for interstellar reddening of $E_{B-V} = 0.6$ using the reddening law given by Seaton (1979), (applicable to diffuse ISM) showed a sudden hump at λ 2180, quite unlike the energy distribution of hot stars.

Since a Zanstra temperature of 26000 K was already estimated by Aitken et al. (1980), HH tried to match the observed fluxes with the computed fluxes using the model atmospheres from Kurucz (1979). HH selected models with $\log g = 4.5$, $T_{\rm eff} = 20000$, 25000, and 30000 K and normal chemical composition (i.e. hydrogen rich) and calculated the emergent fluxes. Since the Seaton (1979) reddening law gave rise to a hump at λ 2180 they modified the reddening law between 2800 Å–1600 Å such that the dereddened flux distribution of the star resembled the model atmospheric flux distribution. The corrected distribution looked very similar to the energy distribution of a normal B2 star in the wavelength range 3000 Å to 1250 Å and led to a stellar temperature estimate of 22000 K.

The above approach of comparing the energy distribution of CPD $-56°8032$ with model atmospheres of hydrogen rich stars seems to be inappropriate since CPD $-56°8032$ is known to be hydrogen-deficient. A comparison of the corrected energy distribution of HH with helium star models (Heber and

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Schönberner, 1980) indicate an effective temperature of ~18000 K which is too low compared to the Zanstra temperature (see Fig. 3). The application of a correction to the reddening law of Seaton seems to be arbitrary and it is not clear how much of reddening is due to the circumstellar material and how much is due to the interstellar medium. With a view to investigate both the emission line spectrum and the extinction properties in UV we obtained additional IUE observations of CPD −56°8032.

2. Observations

The UV observations were obtained with the IUE satellite on July 12, 1987 using LWP camera in the low resolution mode (covering wavelength range 2000 Å–3200 Å) and SWP camera in the high resolution mode to study the emission lines. The details are given in Table 1. These spectra have been reduced using the IUEDR package contained in STARLINK on the VAX-11/780 system at VBO, Kavalur. The flux calibration used for LWP camera was from Cassatella et al. (1988) and SWP high resolution calibration is as given in Cassatella et al. (1986). The visual magnitude (m_v) is estimated from the FES counts as 11.1 using the relations given by Imhoff and Wasatonic (1986). This value is the same as the magnitude estimated when HH observations were obtained on 8 May 1980 ($m_v \sim 11.15$) indicating that the visual flux has not changed much in the meantime.

3. UV spectral features

The high resolution SWP spectrum has a low signal to noise, but the exposure is adequate to show several features. Particularly, there are two strong emission features at λ1761 and λ1908. There is no evidence for the presence of N III] features at λ1748.1, λ1749.7; λ1752.2 and λ1754.0. There is a strong emission feature at λ1760, with a P-Cygni structure (see Fig. 5) corresponding to a strong C II transition. Also the radial velocity of the emission peak is $-69\,\mathrm{km\,s^{-1}}$ quite consistent with the radial velocity observed in the optical spectrum.

The C III] lines at λ1908 show the feature corresponding to λ1908.72 but the λ1906.68 feature is not detectable. The line width indicates that it is a stellar feature and not a nebular feature. The nebular line widths of Hβ from the Echellec spectrum (resolution ~35000) obtained at ESO by one of us (NKR) indicates FWHM corresponding to about $\sim 54\,\mathrm{km\,s^{-1}}$ whereas the FWHM of λ1908 is $160\,\mathrm{km\,s^{-1}}$. Moreover, the radial velocity of C III] λ1908.7 is $-70\,\mathrm{km\,s^{-1}}$ which is also consistent with the radial velocity determination from the optical spectrum (Cowley and Hiltner, 1969). The only resonance lines which could be clearly discerned on the high resolution SWP spectrum is λ1862.78 of Al III (1) in absorption which is shifted by about $260\,\mathrm{km\,s^{-1}}$ to the blue. The other resonance line of Al III (1) at λ1854.7 falls at the edge of the order and it is also blue-shifted.

The conspicuous features of the LWP long wavelength low resolution spectrum are the strong emission features of C II at λ2838, λ2740, and λ2997 of C III. There is no indication of lines of He II or λ2470 of [O II] (Fig. 1). The He I line at λ3187 is also not conspicuous, although He I lines in the optical spectrum show P-Cygni profiles.

The continuum from the 3000 Å to 2000 Å has varied between the observations obtained in July 1987 (Fig. 1). The continuum is lower by about 0.4 mag compared to the observation of HH which indicates that the UV continuum does change although the FES magnitude is roughly the same.

Identification of the emission lines and their fluxes are given in Table 2 along with the fluxes estimated from HH observation as plotted in HH. The emission lines fluxes do seem to remain constant (within errors) even though the UV continuum varied by ~0.4 mag.

4. Analysis

4.1. The stellar temperature

The stellar temperature has been estimated by Aitken et al. (1980) using the dereddened Hβ flux and Morton's method of estimating the Zanstra temperature, as 26000 K. However, this estimation is done using models of stars of normal hydrogen-rich composition. A hydrogen deficient star would have very little Lyman continuum absorption (see Heber, 1986). Hence, the above temperature could be only an upper limit. Unlike in the optical region, the IUE spectrum of CPD −56°8032 is dominated by absorption lines. The low resolution short wavelength IUE spectra obtained by HH are compared in Fig. 2 with those of V 348 Sgr and other helium stars. The absorption features in CPD −56°8032 are very similar to those in V 348 Sgr and BD −9°4395. The T_{eff} of V 348 Sgr is estimated to be between 20000 K to 23000 K (Schönberner and Heber, 1986; Rao and Nandy, 1984) and $\log g \sim 2.5$. For BD −9°4395 the estimated temperature is 23500 K and $\log g = 2.5$ (Drilling et al., 1984). Thus the T_{eff} of CPD −56°8032 seems to have a similar value.

The reddening corrected ($E_{B-V} \sim 0.60$) $B-V$, and $m(2190)-m(2740)$ colors seem to be similar to an unreddened B2V star according to HH which indicates $T_{\mathrm{eff}} \sim 20000$ K.

It is probably relevant to mention that Aitken et al. (1980) pointed out that the infrared luminosity required to explain the observed IR excess (as reradiated stellar flux) seems to be more than the available optical luminosity if $T_{\mathrm{eff}} = 26000$ K. However, with the presence of variable extinction and the uncertainty in bolometric corrections it is possible to provide a just about

Table 1. IUE log

Image no.	Date	Exposure time min	Aperture	m_v(FES)
LWP 11203	July 12, 1987	30	large	11.1
SWP 31335	July 12, 1987	370	large	11.1

m_v is estimated from the relation of Imhoff and Wasatonic (1986).

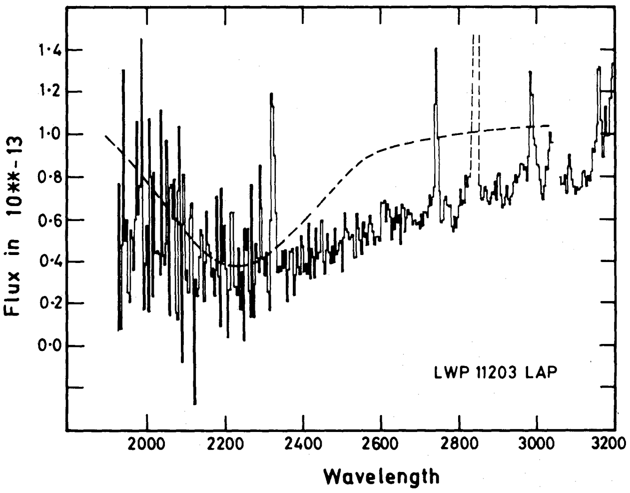

Fig. 1. The LWP spectrum obtained in July 1987. The dashed line indicates the continuum as observed by Houziaux and Heck (1982) in May 1980

adequate IR luminosity with $T_{\rm eff}=26000$ K. We, therefore assume that $T_{\rm eff}$ is between 23500 to 26000 K.

4.2. *UV energy distribution and circumstellar extinction*

The IS reddening estimate essentially comes from the nebular lines and radio continuum. As pointed out earlier, the corrected energy distribution with this reddening $E_{B-V}=0.6$ and the HH reddening law gives a value of $T_{\rm eff}$ which is too low when compared with helium star model atmospheres. Applying either Seaton's as well as modified reddening law of HH with $E_{B-V}=0.6$ to the present LWP observations, not only we get a much lower temperature, but a depression appears in the energy distribution around λ 2500 which suggests the existence of an additional agent causing the extinction. It is known that amorphous carbon dust has a peak in its extinction properties around 2400 Å and the peak wavelength depends on the particle size.

Furthermore, the change in the UV energy distribution observed between the two epochs does not appear to be due to the change in the stellar temperature because the emission line fluxes

Table 2. Observed emission line strengths

Observed wavelength λ	Laboratory wavelength λ	Identification	Line fluxes LWP 11203 erg/s cm^{2}A	Line fluxes HH erg/s cm^{2}A
			$\times 10^{-13}$	$\times 10^{-13}$
3208				
3166	3165.46	C II (9)	2.1 ± 0.2	
	3165.97	C II (9)		
3088:				
3042				
2993	2992.6	C II (8)	3.0 ± 0.25	3.09
2907:	2905.71	C II UV (41)		
	2908.90			
2837	2836.71	C II UV (13)	[b]	17
	2837.60			
2747	2747.28	C II UV (15)	6.6 ± 0.30	6.48
	2746.49			
2730:	2728.71	C II UV (31)		
	2729.21			
	2730.61			
2610				
2605	2604.86	C II UV (33)		
2574:	2574.83	C II UV (24)		
2512	2509.11	C II UV (14)		
	2511.71			
	2512.03			
2470		[O II]	< 0.08	
2327	2326	C II] UV (0.01)	9.6 ± 1.0	5.6[a]
2297	2296.87	C III UV (8)	2.6 ± 0.6	
2218			0.13 ± 0.01	
1908	1908.73	C III UV (0.01)	4.5 ± 0.4	4.3[a]
1760	1760.53	C II UV (10)	(1.1 ± 0.3)[c]	5.5

[a] Line flux estimated from the corrected fluxes given by HH
[b] Saturated
[c] P-Cygni profile, on the emission flux is given here

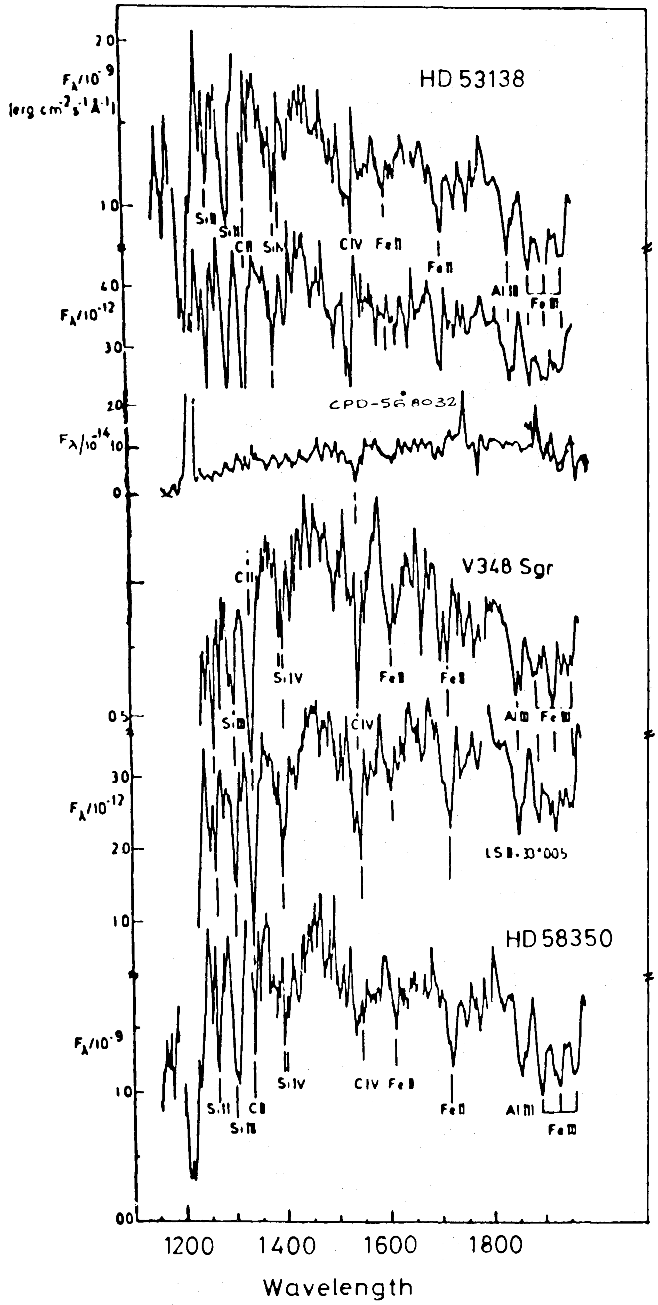

Fig. 2. The short wavelength IUE spectrum of CPD $-56°8032$ (third from top) as obtained by Houziaux and Heck (1982) along with V 348 Sgr, the helium star HD 124448 and normal B Supergiants. (Heber et al., 1984). Note the similarity of C IV, line and Fe III lines in CPD $-56°8032$ and V 348 Sgr

do not seem to change. Moreover, a change in temperature is not expected to cause a depression in the energy distribution around 2500 Å. We, therefore tried to correct the energy distribution of HH as well as the present observations with a combination of reddening curves (1) Seaton's reddening curve applicable to diffuse interstellar medium, and (2) a second component due to the amorphous carbon grains of different sizes, such that the corrected energy distribution could be matched with that of helium star energy distributions with $T_{\rm eff} \sim 25000$ K. Heber and Schönberner (1980) have given the energy distributions of models upto only $T_{\rm eff} = 20000$ K. We have used the dereddened observed energy distribution of the hot helium star HD 160641 as representative of a star of $T_{\rm eff} = 31900$ K as given by Drilling et al. (1984). We used UV observations of HD 160641 obtained by the ANS satellite. The absolute calibration and reddening law as given by Wesselius et al. (1980) have been used. Since the fluxes for the model energy distributions of Heber and Schonberner (1980) were normalized to $\log F_{\lambda V} = -12.43$ the corrected fluxes of CPD $-56°8032$ as well as HD 160641 have been normalized to the same value and are shown in Fig. 3. It is to be noted that the contribution attributed to the ISM (i.e. following Seaton's reddening curve) is also kept constant. We have used the extinction coefficients for various type of submicron amorphous carbon grains determined from the laboratory as given by Bussoletti et al. (1987). The resulting reddening curve upto ~ 3000 Å is essentially the same for both for Seaton's as well as for amorphous carbon grains. The extinction properties differ only in the UV range, < 3000 Å.

Out of the several combinations used, we could fit the energy distribution of HH reasonably well (after dereddening it) with a combination of $E_{B-V} \sim 0.40$ and 0.25 for Seaton's and amorphous carbon grains of the type AC(2) as given by Bussoletti et al. (1987) respectively (Fig. 3). Similarly, the present observations would need a combination of $E_{B-V} \sim 0.40$ and 0.30 of Seaton's and amorphous carbon grains of the type AC(2) to agree with the dereddened energy distribution of HH. The AC(2) of Bussoletti et

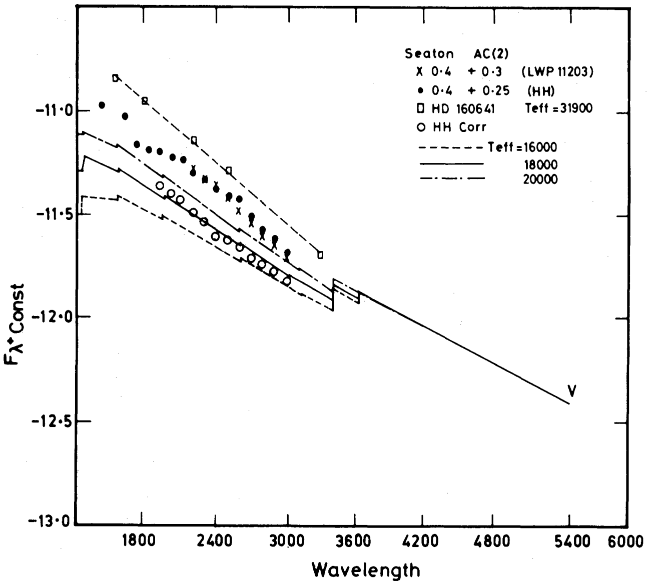

Fig. 3. The dereddened continuum of CPD $-56°8032$ as observed by Houziaux and Heck (1982) compared with the energy distribution of a helium star model (Heber and Schönberner, 1980) normalised at V. The meaning of the various symbols is the following. □ squares: energy distribution of HD 160641 from ANS observations corrected for reddening to represent the energy distribution of a helium star of $T_{\rm eff} = 31900$ K, $\log g = 2.5$; ○ circles: energy distribution of CPD $-56°8032$ corrected for reddening of $E_{B-V} = 0.6$ using a modified Seaton's reddening law as given by HH; ●dots: energy distribution of HH corrected for a reddening of $E_{B-V} = 0.40 + 0.25$ using the reddening curves of Seaton and the curve for laboratory amorphous carbon particles respectively; × crosses: energy distribution of CPD $-56°8032$ LWP 11203 corrected for $E_{B-V} = 0.40 + 0.30$ using the reddening curves of Seaton and laboratory amorphous carbon particles respectively

al. (1987) refers to spheroidal particles of mean diameter of 80 Å produced in an arc between two amorphous carbon electrodes in a controlled Ar atmosphere. The above exercise shows that the amount of small circumstellar grains might change with time.

In addition to the variability of the continuum in the UV, there might be variability of the continuum in the optical region also. From the spectrophotometry obtained in 1979 with AAT, Aitken et al. (1980) estimate $V \sim 11.4$ mag. using the emission free continuum. The emission-free continuum value at $\lambda 5480$ obtained by Houziaux (1986) from the IDS spectrophotometry in 1982 July with 1.5 meter ESO telescope gives a value of $V \sim 11.7$ mag. The continuum flux at $\lambda 4267$ obtained in 1982 July by Houziaux (1986) is 7.6×10^{-14} erg s^{-1} cm^{-2} A^{-1} whereas 1987 July CCD observations by us give a value of 10×10^{-14} erg s^{-1} cm^{-2} A^{-1} (Rao and Houziaux, 1989) although the C II $\lambda 4267$ emission line flux is the same on both occasions $\sim 2.6 \times 10^{-12}$ erg^{-1} cm^{-2}.

4.3. *Emission line spectrum*

As mentioned earlier the emission line flux does not appear to be variable. Particularly, the strong C II emission lines and even the C II] $\lambda 1908$, lines also seem to have roughly the same flux on both occasions. This fact is also true in the optical region, e.g. the C II $\lambda 4267$ flux remained constant between the two observations obtained in 1987 July and 1982 July.

The flux of the nebular lines as characterised by the Hβ flux also seems to be unchanged. The Hβ flux obtained in 1979 by Aitken et al. (1980) is $\log F_\lambda \sim -11.95$ whereas the observations of Houziaux (1986) in 1982 show $\log F_\lambda \sim -11.99$ (F_λ in erg s^{-1} cm^{-2}).

The undetectability of $\lambda 1906$ emission in the CIII] feature in the high resolution spectrum relative to the one at $\lambda 1908.7$, sets a lower limit to the electron density as 10^6 cm^{-3} in the line forming region. Following the calculation of Altamore et al. (1981) another independent estimate of the electron density could be obtained from the ratio N III] $\lambda 1749.7$ to C III] $\lambda 1908.7$ provided there are no abundance anomalies. These two ions are expected to form and survive in the same stellar region because of similar ionization energies and the C III]/NIII] depends little on T_e. Again the absence of N III] lines in our spectra probably puts the limit on $n_e \simeq 10^8 - 10^9$ cm^{-3}.

Recently Kaler (1986) has obtained a relation between electron temperature and the flux ratio of C III] $\lambda 1909$ to CII $\lambda 4267$ in planetary nebulae. As we have mentioned earlier, both these lines occur in CPD $-56°8032$ in the Wolf-Rayet emission line region around the star but not in the nebula. However, the same nebular relationship might apply in the WR emission region also (since the relations are independent of electron density). Taking the values of the C II $\lambda 4267$ flux mentioned earlier from observations obtained in July 1987 (Rao and Houziaux, 1989) and the flux of C III] $\lambda 1908$ measured by us (given in Table 2) and after correcting for the reddening of $E_{B-V} \sim 0.4 + 0.3$ (Seaton + AC(2)), we get the observed line ratio R_C ($\lambda 1908/\lambda 4267$) as 3.08 and $\log R_C \sim 0.4$ (± 0.3). This value is similar to $\log R_C = 0.64 \pm 0.3$ given by Kaler (1986) for the other WC 11 object M 4-18. Even in the case of M 4-18, it is likely that these two lines are formed in the emission line region surrounding the star but not the nebula. It should be remarked that the value of E_{B-V} estimated by Goodrich and Dahari (1985) is too high. Use of the measured radio flux at 10 GHz (15 ± 6 mJy Purton et al., 1981) and the Hβ flux (Goodrich and Dahari, 1985) lead to an estimate of E_{B-V} between 0.56 to 0.41 which indicates the values of $\log R_C \sim 0.3$ if Seaton's reddening law is used.

The empirical fit to the observed value of electron temperature as a function of $\log R_C$ (Fig. 1 of Kaler, 1986) gives a value of electron temperature of 7000 K for the line emitting region for CPD $-56°8032$ (similar to that for M 4-18). The error in this estimate is hard to assess. Moreover the applicability of this relation from planetary nebulae to Wolf-Rayet envelopes is not beyond doubt (as it probably depends on the assumption that $\lambda 4267$ line is due to recombinations alone). Dahari and Osterbrock (1984) estimate $T_e \sim 1.05 \times 10^4$ K for the emission region in V 348 Sgr from a LTE analysis of C II emission lines.

5. Stellar wind and mass loss rate

It was pointed out by Cowley and Hiltner (1969) that in the optical region the lines of He I and O II show P-Cygni profiles indicative of mass loss, although the lines of the dominant ion C II do not show the P-Cygni characteristics. The strongest emission lines in the spectrum are C II $\lambda 7236$ and $\lambda 4267$ and neither have a P-Cygni nature. However, Thackeray (1977) mentioned a P-Cygni profile for $\lambda 6578$ of C II with the absoption dip shifted from the emission peak by -173 km s^{-1}. The spectrum obtained by Herbig (1986) with CTIO 4-meter telescope also shows a P-Cygni profile for $\lambda 6578$ with the absorption shifted by -160 km s^{-1} from the emission peak. In the UV region P-Cygni type line profiles are not seen in the low resolution (~ 6 Å) IUE spectra but our high resolution SWP spectrum shows the C II line of $\lambda 1760.6$ having a P-Cygni profile with a radial velocity difference between emission and absorption of -240 km s^{-1}. The edge velocity is -350 km s^{-1} relative to the emission peak (Fig. 4). Thus the only C II lines which show P-Cygni profiles are those transitions whose lower levels are the upper levels to the resonance lines, e.g. $\lambda 1760$ with $\lambda 1335$ and $\lambda 6578$ with $\lambda 1037$.

The only resonance line which could be discerned with some confidence in our spectrum is $\lambda 1862$ of Al III (1) which shows a blue shifted absorption dip with a blue edge occuring at -380 km s^{-1} from the emission. Although the spectrum is weak, the C II resonance lines at $\lambda 1335$ seem to be present and the blue-edge velocity seems to agree with Al III value and indicates that the terminal velocity (Fig. 5) probably is close to this edge value.

But the optical He I lines which show P-Cygni profiles show a much smaller edge velocity.

The profile of C II 1760 is shown in Fig. 5 converted in terms of the continuum flux and $W = V - V_0/V_\infty$ where V_∞ is taken as the edge velocity of Al III lines.

Olson (1981) has proposed a method to estimate the mass loss rate and stellar wind properties from the P-Cygni line profiles of the subordinate lines arising from the excited levels that are upper levels for the strong resonance lines. We applied this method to C II $\lambda 1760.5$ line profile to estimate the mass loss rate. We compared the theoretically computed profiles of Olson (1981) for various velocity laws with observed profiles till a reasonable match was obtained. The basic variable is the radial optical depth which is expressed in terms of the atomic constants. The stellar parameters are put into one constant T and the remaining factors of the profile function depend on the velocity law used. Line profiles were computed theoretically for a range of T values and three velocity laws. We proceeded by matching the theoretical

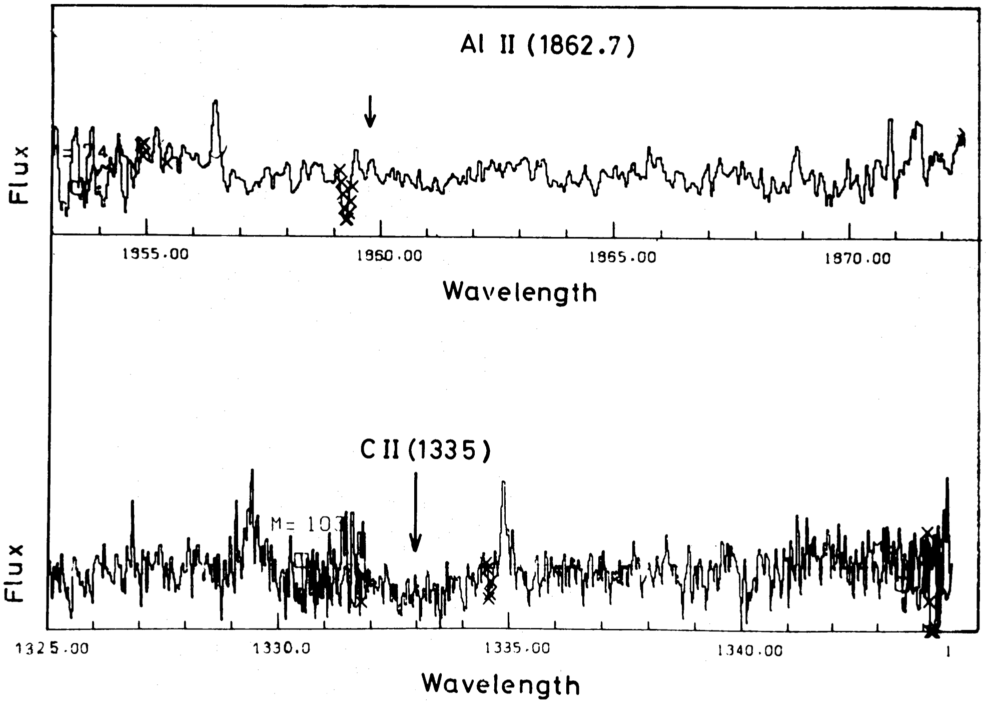

Fig. 4. The high resolution IUE spectrum in the region of λ 1862 Al III and λ 1335 C II resonance lines, which show blue-shifted absorptions. The blue edge of Al III λ 1862.7 is assumed to represent the terminal velocity of the stellar wind

line profile with the observed profile to estimate the values of T and β where the T parameter is related to mass loss and characterises the velocity law; the radial velocity was assumed to be given by $W(x)=0.02+0.98\ (1-1/x)^{\beta}$ where $x=r/R_*$ and $W(x)=V(x)/V_{\infty}$

$$T=2.12\times 10^{-13} f\lambda_0 \frac{W_l}{W_g}\lambda_1^3 F_{\nu 1} A_E \dot{M}_6 \left(\frac{R_{\odot}}{R_*}\right)\left(\frac{1000}{V_{\infty}}\right)^2 g_i \frac{1.35}{\mu}$$

where f is the oscillator strength of the transition, λ_0 is the wavelength of the transition in Å and λ_1, ν_1 are the wavelength and frequency of the line that photoexcites the level 1. $F_{\nu 1}$ is the monochromatic stellar flux. w_l and w_g are the statistical weights of the level and the ground level. V_{∞} is the terminal velocity in km s^{-1}, g_i is the fractional abundance of the ion $=n(\text{ion})/n$ (element); A_E is n/n_{tot}, μ is the mean molecular weight. When applying this method to C II λ 1760, the various parameters are estimated as follows. The λ_0 is 1760.53 Å and λ_1, the resonance transition which populates the lower level of the transition is λ 1335.338. w_l and w_g are statistical weights of the term, and have the values of 10 and 6 respectively. The oscillator strength $f=0.01216$ is given by Nussbaumer and Storey (1981). The material is assumed to have the composition of helium star as estimated for BD $-9°4395$ (Heber, 1986) which gives $A_E=6.55\times 10^{-3}$; and the terminal velocity $V_{\infty}=-380$ km s^{-1}. The value of R_*, the stellar radius for CPD $-56°8032$ is estimated as follows. From the spectral similarity with BD $-9°4395$ the $\log g$ value is assumed as 2.6 and the mass as 0.55 $m_{\odot}$ corresponding to mass of central stars of planetary nebulae which leads to $R_* \sim 6\,R_{\odot}$. From the infrared excess observed, Aitken et al. (1980) estimated that the minimum stellar luminosity required to produce the IR flux is $2.25\times 10^3\,D^2\,L_{\odot}$ (D in kpc). By adopting the size of the nebula of 1.″3 (Roche et al., 1986) and using the IRAS dust temperature (mainly based on 60μ, 100μ flux) and linear nebular radius relation of Pottasch et al. (1984) for planetary nebulae, the distance estimated is 2.36 kpc, which would make the luminosity as $12.53\times 10^3\,L_{\odot}$ with an assumed $T_{\text{eff}}\sim 25000$ K. R_* is estimated as $6.2\,R_{\odot}$.

The stellar flux $F_{\nu 1}$ is estimated from the model atmosphere of helium stars. For $T_{\text{eff}}=20000$ K and $\log g=2.5$, $F_{\nu 1}$ is 1.04×10^{-3} erg s^{-1} cm^{-2} Hz^{-1} (Heber, 1986). For HD 160641, the $F_{\nu 1}$ estimated by Drilling et al. (1984) with $T_{\text{eff}}=31900$ and $\log g=2.5$ as 5.1×10^{-3} erg s^{-1} cm^{-2} Hz^{-1}. We adopt a value of 2×10^{-3} erg s^{-1} cm^{-2} Hz^{-1} for CPD $-56°8032$ and the composition is assumed to be mostly He I thus the value of μ is 4.

The fits of the theoretical profile to the observed profile show that $T\sim 100$ and $\beta \sim 1$ seem to be appropriate, although $T\sim 100$ and $\beta\sim 2$ would not give too bad a fit. Thus the mass loss rate is obtained as $\dot{M}\sim 1.09\times 10^{-7}/g_i\,m_{\odot}$ yr^{-1} with $R_*=6\,R_{\odot}$.

If most of the carbon is assumed to be in the form of C II and C III, and if they are in the ratio 0.7 to 0.3 then the mass loss rate is $1.56\times 10^{-7}\,m_{\odot}$ yr^{-1}. An estimation of the uncertainty in this mass loss rate is not easy to assess but could be within a factor ~ 5. The terminal velocity of the wind estimated here seems to be lower compared to other WC central stars of planetary nebula, (Kaler et al., 1989) but higher resolution and better signal to noise IUE spectra are needed to reduce the uncertainty, however the value estimated above is not likely to change very much. As a comparison, He 2-99 which is a PN with a central star classified as WC9 and has $T_{\text{eff}}\sim 26000$ K estimated by Kaler et al. (1989) shows a half-width at zero intensity for λ 4267 of ~ 740 km s^{-1} whereas CPD $-56°8032$ shows a λ 4267 half-width of ~ 227 km s^{-1} (Rao and Houziaux, 1989) which is a factor of three lower. The terminal velocity of He 2-99 is estimated as ~ 1200 km s^{-1}. If this factor of three reduction is applied, the terminal velocity of CPD $-56°8032$ is expected to be ~ 400 km s^{-1} which is quite consistent with the value used.

Sw St 1 a WC10 star with a compact PN around it has a terminal velocity of 1950 km s^{-1}. In the case of CPD $-56°8032$ although the terminal velocity is lower, the mass loss estimated above is comparable to that of other WC9 and WC10 stars e.g.

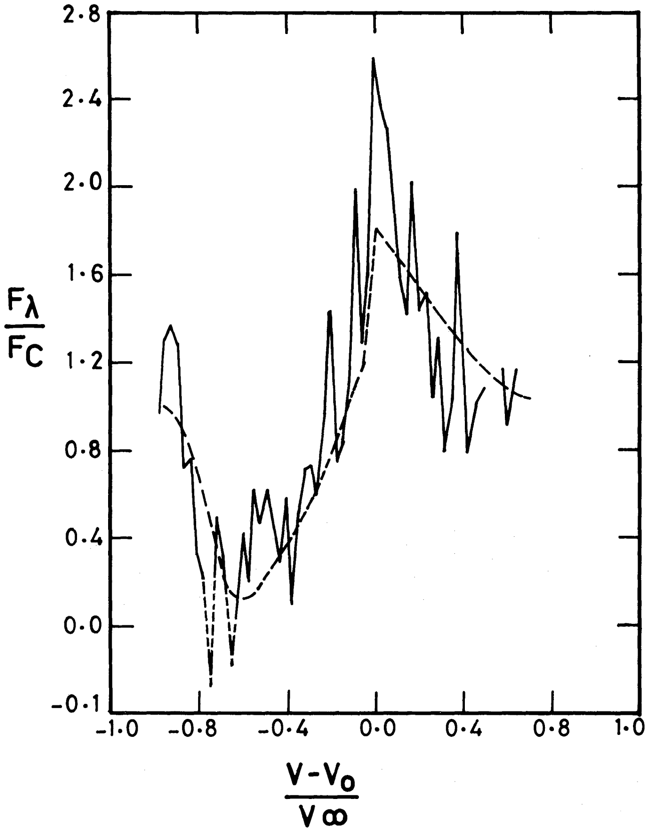

Fig. 5. The observed P-Cygni line profile of λ 1760.53 C II (continuous line) superposed on the theoretical profile with $T=100$ and $\beta=1$ as given by Olson (1981) (dashed curve)

for Sw St 1 it is $6\text{–}7\times10^{-8}\, m_\odot\,\mathrm{yr}^{-1}$ (de Freitas Pacheco and Veliz, 1987).

6. Comparison with other WC11 stars

The UV spectra of the two other WC11 stars M 4-18 and V 348 Sgr obtained by Goodrich and Dahari (1985) and Heck et al. (1983) respectively are shown in Fig. 6 along with that of CPD −56°8032. They show a remarkable similarity; particularly the spectra of M4-18 and CPD−56°8032 closely resemble each other. The photospheric features like C IV also seem to be very similar (Fig. 2). In the case of V 348 Sgr the circumstellar absorption lines are more enhanced and the emission lines are weak (Fig. 6). They also show a gradual change in the excitation and in the emission line to the continuum ratio from CPD−56°8032 to V 348 Sgr. In CPD−56°8032 the C II emissions are much stronger relative to the continuum when compared to M 4-18. In addition, the C III λ 2297 feature is present whereas in V 348 Sgr the C II emission is weak or absent. The circumstellar absorptions due to Fe II, Mg II are present in all three stars but are much stronger in V 348 Sgr. The stellar temperature for M 4-18 was estimated by Goodrich and Dahari (1985) from the energy-balance method as T 22000 K ± 2000 K.

The UV energy distribution of V 348 Sgr has been fitted by Schönberner and Heber (1986) with a helium star model of $T_{\mathrm{eff}}=20000$ K and $\log g=3$ after correcting for the reddening of $E_{B-V}=0.45\pm0.15$ with a combination of 0.4 Seaton's and 0.15 caused by amorphous carbon grains. A similar approach is applied here for CPD−56°8032. In both stars the amorphous carbon grains are probable constituents of the circumstellar dust.

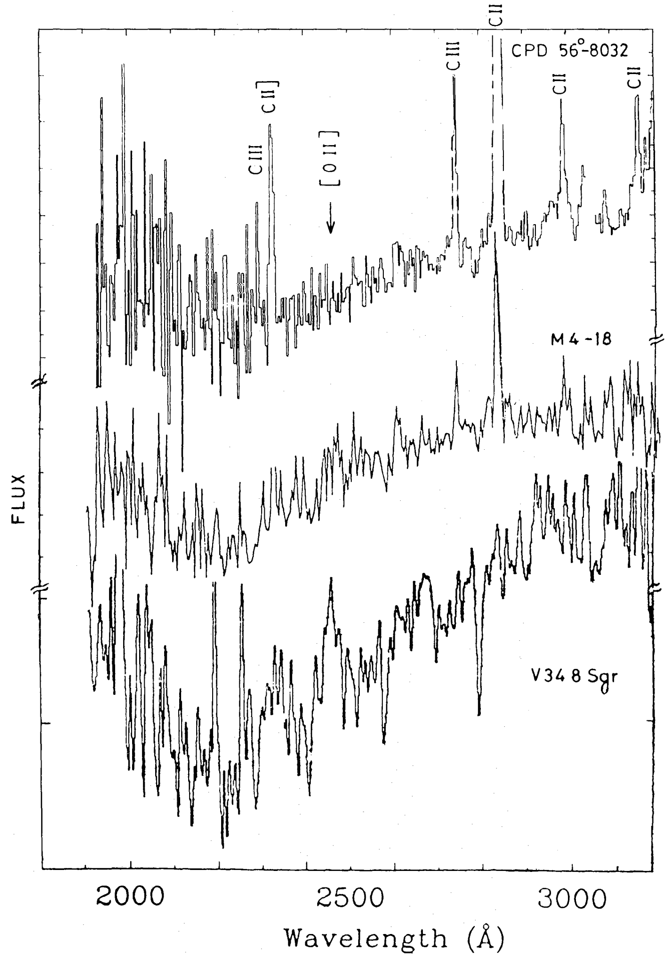

Fig. 6. The IUE spectra in the region 2000–3000 Å, of the three WC 11 stars CPD −56°8032 (top – LWP 11203), M 4-18 (LWR 8401 – Goodrich and Dahari, 1985) and V 348 Sgr (bottom – LWR 11604, Heck et al., 1982). Note the variation in the emission line strength from top to bottom and the prominence of absorptions in the bottom spectrum (V 348 Sgr)

In the long wavelength IUE spectrum (Fig. 6) there appears to be obvious differences in the strengths of forbidden lines (presumably from the nebula). In CPD−56°8032 the λ 2326 C II] feature is quite strong which is absent in M 4-18 and V 348 Sgr (The sharp emission like feature occurring at λ 2326 in LWR 8401 of M 4-18 is an ion hit or defect (Goodrich and Dahari, 1985; Stickland, 1988 personal communications)). This feature is suppressed in Fig. 6. However the comparison of the spectra of these stars (Fig. 6) shows that there is an emission feature V 348 Sgr corresponding to λ 2470 of [O II] which is weak or absent in M 4-18 and CPD−56°8032. Although HH mention that [O II] λ 2470 is present in their IUE spectrum of CPD−56°8032, it is not obvious in our spectrum. If C II] λ 2326 also comes from the nebula then the ratio of λ 2326 to λ 2470 emissions would be a good indicator of $\mathrm{C}^+/\mathrm{O}^+$ ratio in the nebulae independent of reddening. An estimate of the $\mathrm{C}^+/\mathrm{O}^+$ ratio in V 348 Sgr from the λ 2470 emission mentioned above is 0.06 assuming $T_e\sim1.25\times10^4$ K and $N_e\sim10^3$ (Dahari and Osterbrock, 1984). According to the analysis of Goodrich and Dahari (1985), M 4-18 is supposed to have a high O abundance, but still the λ 2470 feature is not conspicuous in the UV spectrum of M 4-18. The expected line flux estimated using $E_{B-V}=0.4$ and reddening law of Seaton and the observed flux of [O II] $\lambda\lambda$ 7319, 30 from Goodrich and Dahari (1985) is $\sim 3\times10^{-14}$ erg s^{-1} cm^{-2} (which is about half the flux of C II λ 2747). The sharp feature in Fig. 6 at λ 2470 could correspond to this. A better estimate of carbon abundance in the CPD $-56°8032$ nebula needs high resolution observation of λ 2326 feature to discern the nebular C II] lines.

Cohen and Jones (1987) added another member IRAS 21282 +5050 to this class of WC11 CPNs. This source however differs from other WC11 stars in having 5.8 mag visual extinction and a large and an extensive molecular envelopes with strong CO (1–0) and (2–1) emissions (Likkel et al., 1988). It also shows strong dust emission features at 7.7, 8.7, 11.3μ which are attributed to polycyclic aromatic hydrocarbon (PAH) molecules. All the WC11 stars show these features except V 348 Sgr, which shows a very weak 3.3μ feature. The central star for IRAS 21282+5050 is classified to be WC11, showing λ 4686 He II, C IV, O IV features which makes this star hotter than CPD $-56°8032$. Another major difference is the extensive molecular envelope around IRAS 21282+5050 for which the estimated size is 10″ and the CO mass rate is $\dot{M}\sim1.5D^2 10^{-5} m_\odot$ yr^{-1} (D in kpc) with an expansion velocity V_e of $\sim$16.5 km s^{-1}.

Knapp et al. (1989) detected CO (2–1), and Nyman (1989) CO (1–0) in CPD $-56°8032$. Although the expansion velocity V_e is roughly the same for CPD $-56°8032$ (i.e. $\sim$17 km s^{-1}) and IRAS 21282+5050, the mass loss rate and the ratio T_{mb} (Co)/F (FIR) of the brightness temperature to the far infrared flux is more than an order of magnitude smaller in both CPD $-56°8032$ and He 2-113 (Likkel et al., 1988). It is likely that IRAS 21282 is in an earlier evolutionary stage than CPD $-56°8032$. The mass-loss rate estimated by Knapp et al. (1989) is $1.6\times10^{-6} m_\odot$ yr^{-1} assuming a distance of 630 pc. This estimate is supposed to reflect the mass-loss rate in the AGB phase, which appears to be too low. In the plot of M(CO) versus log $S_{25\mu}/S_{12\mu}$ (Fig. 1 of Knapp et al., 1989), CPD $-56°8032$ occurs in a position too far down reflecting too low an $\dot{M}$ relative to other PNS. If the distance 2.3 kpc is used (as estimated in Sect. 5), then the $\dot{M}$ ($\sim2.13\times10^{-5} m_\odot$) is more consistent with the other PNS.

7. Discussion

The UV observations of CPD $-56°8032$ show that the continuum of the star does vary though the emission line fluxes do not. This is also true in the optical region. The fact that the FES magnitudes are roughly constant, even though the UV fluxes have changed by $\sim$0.4 mag. is probably due to the domination of emission lines in the broad wavelength band of the FES where the continuum is much weaker than the emission lines.

These variations could be interpreted as due to a change in the amount of circumstellar dust and may be to some extent even to the particle size. Thus, it shows a great similarity with V 348 Sgr which shows a much larger RCrB type variability. In addition, both objects require (and also RCrB) extinction due to amorphous carbon grains to explain the energy distribution. To explain the variation of the continuum without changing the emission line flux might need a special kind of geometry for the distribution of dust.

One of the problems regarding the IR emission in CPD $-56°8032$ is that the IR luminosity required seems to be higher than the stellar luminosity (Aitken et al., 1980). The observed IR luminosity is $2.25\,10^3\,D^2 L_\odot$ (D in kpc). The dereddened magnitudes and $T_{\rm eff}=25000$ K could produce, with proper bolometric correction and small variability in V magnitude, just about adequate stellar luminosity to match the IR, which implies almost 100% conversion of stellar luminosity to infrared. One possibility out of this dilemma is to increase th $T_{\rm eff}$ of the star to $\sim$33000 K but this seems to be inconsistent for several reasons. The other possible alternative is to invoke neutral extinction caused by bigger particles mainly effecting the star (but not the nebula since the Hβ-radio flux relation seems to be consistent with reddening). The presence of such big particles has been invoked in the so called proto planetaries like HD 161796, HR 4049 to explain large infrared excesses (Lamers et al., 1986). In particular, the presence of 11.3μ emission feature in HR 4049, which is also prominently present in CPD $-56°8032$ supports this similarity. Most of the IR luminosity in CPD $-56°8032$ comes from hotter dust which is presumably closer to the star.

Pottasch et al. (1986) have plotted the 6 cm radio flux versus infrared flux for planetary nebulae including the proto and compact planetaries, which shows positive correlation between the free-free flux and the IR flux. In this figure, CPD $-56°8032$ occupies a place quite far from the mean corresponding to the 6 cm flux density (26 mJy – Purton et al., 1981), showing that it has too much IR luminosity for the amount of ionized gas. This trend is also seen in other hydrogen deficient nebulae like A 30 and A 58 (Pottasch et al., 1986; Rao et al., 1987). The CO rotation lines seem to imply that the cool gas to dust ratio is an order of magnitude smaller than in the other compact PNS like IRAS 21282. It appears that somehow CPD $-56°8032$ has very efficiently produced (or is producing) circumstellar dust (or has retained it) whereas the gas is depleted.

The preliminary estimate of the nebular expansion/velocity from the Hβ line (half the FWHM) corresponds to 26 km s^{-1} (Rao and Houziaux, 1989) which is higher than the CO molecular gas expansion velocity of $\sim$17 km s^{-1} (Knapp et al., 1989). Since the nebular expansion velocity is believed to increase with age in PNS, this probably implies that CPD $-56°8032$ is more evolved in particular. When compared with other compact PNS like Sw St 1 which has a nebular expansion velocity of 9 km s^{-1}.

The observed terminal velocity V_∞ of the winds from the central stars of planetary nebulae increase with $T_{\rm eff}$ (Kudritzki and Mendez, 1989). This is attributed to the radiation-driven winds being present in the outer layers of CSPN, since in this case the terminal velocity increases with the surface escape velocity and thus with $T_{\rm eff}$ (Kudritzki and Mendez, 1989). The low value of the terminal velocity $\sim$380 km s^{-1} obtained for CPD $-56°8032$ also indicates a low $T_{\rm eff}$. The terminal velocity seems to undergo a dramatic change within about one spectral subclass, going from 1200 km s^{-1} for He 2-99, and 1950 km s^{-1} for Sw St 1 (WC 9) to 380 km s^{-1} for CPD $-56°8032$ which is a WC10/WC11 star (Heap, 1982). The estimate of $V_\infty/V_{\rm esc}$ gives a value $\sim$2 rather than $\sim$3.5 expected from Kudritzki and Mendez's calculations (their Fig. 20). It is not clear whether the stellar wind is driven by radiation at this low $T_{\rm eff}$.

The sequence of WC11 stars shows a decrease in the degree of excitation of the emission line spectrum between CPD $-56°8032$ to M 4-18 to V 348 Sgr indicative of a change in stellar temperature from 25000 K to 20000 K. The inspection of Fig. 6 also shows a strengthening of circumstellar absorption features of Fe II (multiplets 78, 63, 62 etc.) apart from the resonance lines of Fe II, Mg II which might have a contribution from interstellar medium. A list of circumstellar features for V 348 Sgr has already been given by Heck et al. (1982). Further optical and UV observations (higher resolution) are needed before a physical model can be developed.

Acknowledgements. It is a pleasure to thank Dr. Cassatella for arranging the IUE observing. We are grateful to Dr. G.H. Herbig and L. Houziaux for unpublished information and general encouragement. We would like to thank Dr. David Stickland for checking the IUE image of M 4-18 at our request.

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