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8–13 μm spectra of very late type Wolf–Rayet stars

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Summary. 8–13 μm spectra are presented of the late Wolf–Rayet stars, Ve 2-45 (WC9), CRL 2104 (WC8), He 2-113 (WC10) and CPD–56° 8032 (WC10). Both WC10 stars show the unidentified feature at 11.25 μm and one of them that at 8.6 μm; their spectra resemble those of some planetary nebulae. These features are absent in the WC8/9 stars, whose spectra, together with their infrared photometric data, can be understood in terms of ~ 900 K blackbody spectra subject to some interstellar silicate absorption and with a small excess beyond 10 μm, perhaps due to SiC grains. The WC10 objects are characterized by much lower dust temperatures and their evolutionary status appears to be very different from that of the WC8/9 stars.

1 Introduction

Infrared excess emission has been detected in a number of Wolf–Rayet stars. In the WN and early WC types this has been attributed to free–free radiation. In the case of WC9 stars it is found that the excess is best fitted by thermal emission by circumstellar dust (Allen, Harvey & Swings 1972; Gehrz & Hackwell 1974; Cohen, Barlow & Kuhi 1975). We present spectrophotometry from 8 to 13 μm of four objects which may be related by the Wolf–Rayet phenomenon. Ve 2-45 and CRL 2104 are WC9 and WC8 stars which are surrounded by circumstellar dust shells and suffer considerable visual extinction. CPD–56° 8032 and He 2-113 are two objects which have been classified as WC10 stars by Webster & Glass (1974), cooler than WC9, and which have substantial infrared excesses.

1.1 *Ve 2-45*

Photometry by Gehrz & Hackwell (1974) of this object, a WC9 star, shows an excess well-fitted by blackbody emission and attributed to circumstellar dust emission. Cohen & Vogel (1978) have obtained spectra between 2 and 4 μm showing an essentially smooth continuum with no definite emission lines. After dereddening for $A_V = 2.3$ mag interstellar extinction

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they find a best fit to a 900 K blackbody. Cohen & Kuhi (1977) suggest circumstellar extinction of $A_V = 4.7$ mag, and that it is a binary system with an early-type companion.

Thomas, Robinson & Hyland (1976) also observed this object photometrically from 2 to 12 μm finding a good fit to a blackbody near 1000 K but with an excess at 11 μm which they attributed to emission from SiC grains, as seen in some carbon stars.

1.2 *CRL 2104*

This is a heavily reddened WC8 star identified by Cohen & Kuhi (1976) from optical scanner spectra. The presence of an O-type companion was indirectly deduced from dilution of the emission lines. The extinction to this object derived by Cohen & Vogel (1978) was $A_V = 13$ mag. 2–4 μm spectrophotometry again shows a featureless continuum indicating a blackbody excess with a dereddened temperature of about 850 K for $A_V \sim 3.5$–6.0. Photometric points from the CRL survey also indicate a blackbody excess, although the 20 μm flux in this direction is somewhat high.

1.3 *CPD –56° 8032*

This is an emission line object whose optical spectrum is described by Cowley & Hiltner (1969) and red spectrum out to 8200 Å by Thackeray (1977). It displays strong lines of C II, C III and He I which are considerably narrower than those found in other Wolf–Rayet stars. In addition, forbidden lines of [O I], [O II], [N II] and [S II] are present but no [O III], indicating a low excitation. Infrared photometry by Webster & Glass (1974) and Cohen & Barlow (1980) shows a strong excess with a peak shortward of 8 μm. Cowley & Hiltner regard it as being probably hydrogen deficient. Radio observations by Purton *et al.* (1981) indicate an optically thin free–free spectrum between 2.7 and 14.7 GHz, with a flux of 26 ± 4 mJy at 5 GHz. Optical spectrophotometry obtained by one of us (MJB), using the Image Photon Counting System and RGO Spectrograph on the AAT, yields the following fluxes for the narrow nebular hydrogen lines (in erg cm^{-2} s^{-1}): $\log F(\mathrm{H}\alpha) = -11.20$ and $\log F(\mathrm{H}\beta) = -11.95$. For $R = 3.1$ and using the form of the Whitford reddening law given by Miller & Mathews (1972) the Hα to Hβ flux ratio yields $A_V = 1.86$, whilst the radio to Hβ flux ratio yields $A_V = 1.85$ (case B conditions with $T_e = 10^4$ were assumed).

1.4 *He 2-113*

This object (also known as Hen 1044) bears a remarkable resemblance to CPD–56° 8032 both optically and in the infrared. The optical spectra compared by Webster & Glass are very similar except that the nebular hydrogen lines in this object are stronger relative to the continuum. The infrared photometry by Webster & Glass (1974) and Cohen (1975) closely follows the flux distribution of CPD–56° 8032. The radio observations of Purton *et al.* (1981) indicate an optically thin free–free spectrum above about 9 GHz, with a 14.7 GHz flux of 160 ± 10 mJy. Webster (1969) measured $\log F(\mathrm{H}\beta) = -11.83$ and $\log F(\mathrm{H}\gamma) = -11.94$, which yield a negative extinction for case B conditions. Our optical spectrophotometry, obtained as for CPD–56° 8032, yields $\log F(\mathrm{H}\beta) = -11.82$, $\log F(\mathrm{H}\gamma) = -12.38$ and $\log F(\mathrm{H}\delta) = -12.68$. The H$\beta$ flux is in good agreement with that of Webster and our Hβ, Hγ and Hδ fluxes are self-consistent with case B conditions and $A_V = 3.2$. The radio to Hβ flux ratio yields $A_V = 3.4$.

2 Observations

The measurements were obtained with the AAT 3.9-m telescope in 1978 July using the UCL cooled grating spectrometer, with a 3.6 arcsec aperture. The observational techniques were as used in earlier work (e.g. Aitken *et al.* 1979a). Absolute flux calibration was relative to β Gru and is considered accurate to 20 per cent; wavelength calibration was obtained from sky emission features and is accurate to ±0.02 μm. The spectra are shown in Fig. 1 where it is seen that the WC10 spectra differ from those of the WC8 and 9 stars by the appearance of features at 8.6 and 11.25 μm. The observations of Ve 2-45 and CRL 2104 were made under rather poorer seeing conditions than those of CPD–56° 8032 and He 2-113, and the weak structure between 10.5 and 12 μm seen in the former pair may be due to this.

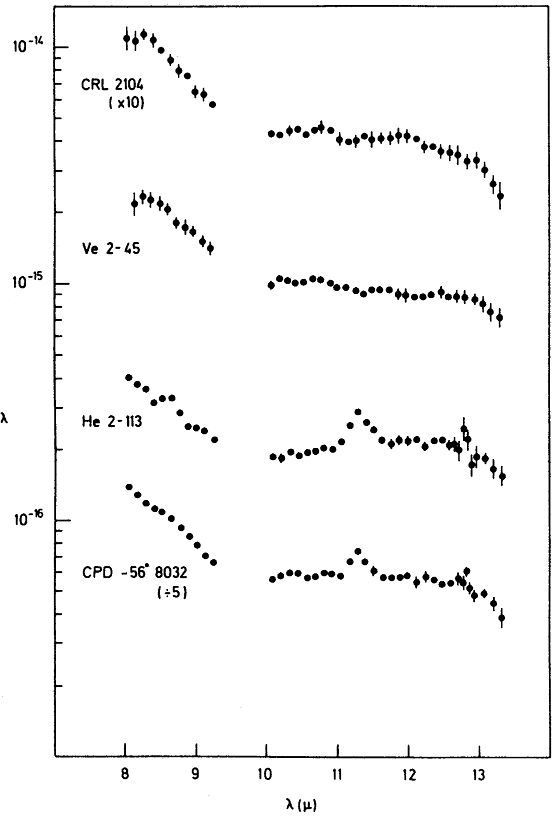
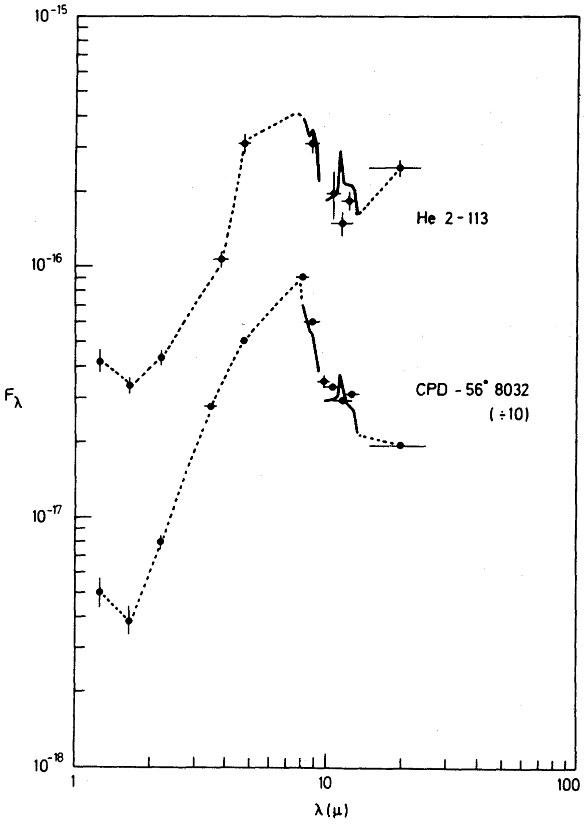


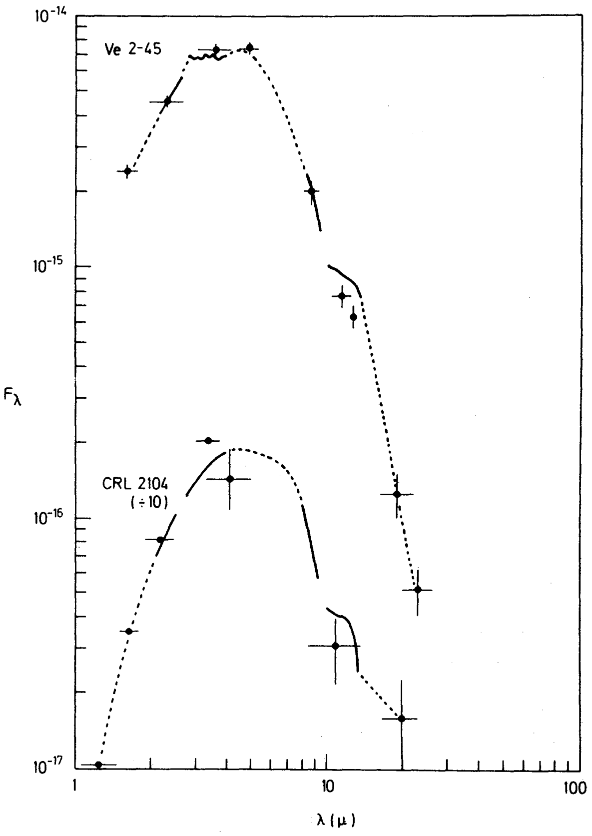
Figure 1. 8–13 μm spectra of Wolf–Rayet objects. Resolution is $\Delta\lambda = 0.15$ μm, except in the region of the [Ne II] emission line at 12.8 μm in the spectra of He 2-113 and CPD–56° 8032, where the resolution is 0.045 μm. Errors are one standard deviation of the mean; flux is in W $\mathrm{cm}^{-2}\,\mu\mathrm{m}^{-1}$.

3 Infrared continuum emission

The 8–13 μm spectra of the four objects, shown in Fig. 1, are broadly similar, with a roughly $F_\lambda \propto \lambda^{-4}$ distribution between 8 and 10 μm, although the WC10 stars have narrow emission features at 11.25 and 8.6 μm whilst the WC8 and WC9 stars have smooth continua. However, when the overall infrared flux distributions of the two types of objects are compared (Fig. 2) they can be seen to be radically different. The flux distributions of Ve 2-45 and CRL 2104 resemble smooth blackbodies with some silicate absorption at 10 μm, whereas the infrared flux distributions of the WC10 stars are non-grey and apparently highly peaked in the 5–10 μm region.


10^-15
10^-16
10^-17
10^-18
F_λ
He 2-113
CPD - 56° 8032
(÷10)
1
10
100
λ(μ)

(a)


10^-14
10^-15
10^-16
10^-17
F_λ
Ve 2-45
CRL 2104
(÷10)
1
10
100
λ(μ)

(b)

The observed visual extinctions of $A_V = 1.85$ and $A_V = 3.3$ towards CPD–56° 8032 and He 2-113 respectively are such that the corresponding silicate absorption features would have only a small effect on their spectra between 8 and 13 μm. Their 8–13 μm spectra, together with the photometric measurements, strongly suggest that the WC10 objects have infrared flux distributions similar to NGC 7027 or HD 44179 and that the rise from 9 to 8 μm in their spectra should be associated with the broad peak centred at 7.7 μm seen in those sources exhibiting the 11.25 and 8.6 μm features which have been studied spectrophotometrically in the 4–8 μm regions (e.g. Merrill 1978). Inspection of Fig. 1 indicates that CPD–56° 8032 has a weaker 8.6 μm feature than He 2-113 and that the relative strengths of the 8.6 and 11.25 μm features may differ in the two objects.

Aitken *et al.* (1979b) have fitted the 8–13 μm spectra of a number of planetary nebulae with linear combinations of four astronomically determined emissivity functions representing the grain materials graphite, silicate, SiC, and the 'Orion Bar' spectrum (Aitken *et al.* 1979a) characteristic of the narrow features. The spectra presented here have 11.25 μm features considerably less prominent relative to the rising edge near 8 μm, attributed to the 7.7 μm feature, than the 'Orion Bar' emissivity function, which has an 11.25 μm feature of the same order as the rising edge at 8 μm. Therefore to fit the WC10 spectra with the 'Orion Bar' function a great deal more weight has to be applied to the 9 μm end of the emissivity curve, which can only be achieved, assuming thermal emission, by invoking unrealistically high temperatures; the narrow features may in any case be due to non-thermal processes (Allamandola & Norman 1978). It is clear that this simple approach is not sufficient here. The 11.25, 8.6 and 7.7 μm features may well vary in relative strength from object to object and are not necessarily caused by the same material or process, although clearly the environment that produces one of them is such that the others may also arise.

Attempts to fit the observed 8–13 μm spectra of Ve 2-45 and CRL 2104 with Planck functions having the temperatures suggested by Cohen & Vogel and silicate absorption described by the Trapezium emissivity function (Forrest, Gillett & Stein 1975) do not give acceptable fits. Cooler blackbodies together with silicate absorption do give better fits, with best fit parameters of $T = 700$ K and $\tau_{10\,\mu\mathrm{m}} = 0.58$ for CRL 2104 and $T = 620$ K and $\tau_{10\,\mu\mathrm{m}} = 0.64$ for Ve 2-45. Significant departures from the observed spectra occur near 13 μm, where the spectra are falling off rapidly. However, a blackbody at $T = 620$ K is inconsistent with the 2–23 μm photometry of Ve 2-45, which is well fitted by a blackbody at $T = 900$ K. In addition a 10 μm optical depth of 0.6 implies some 8 mag interstellar extinction, given a standard reddening law and an assumed ratio of $A_V/\tau_{10\,\mu\mathrm{m}} = 14$ (Gillett *et al.* 1975; Rank *et al.* 1978). This is somewhat high compared to the 2.3 mag interstellar extinction derived by Cohen & Kuhi (1977; the circumstellar material is thought to be carbon-rich and should not give any silicate absorption).

Alternatively, if we deredden the spectra by the amounts of silicate necessary to produce 8–10 μm slopes equivalent to the temperatures of Cohen & Vogel, the 10 μm optical depths required are 0.3 and 0.6, for Ve 2-45 and CRL 2104 respectively. Projecting the blackbodies through the dereddened points leaves an excess in the 11–12 μm region which may possibly

Figure 2. (a) Observed flux distributions of the WC10 objects. The photometric measurements at wavelengths less than 3.6 μm are from Webster & Glass (1974). The longer wavelength points are from Cohen & Barlow (1980) for CPD–56° 8032; and from Cohen (1975) for He 2-113, after renormalization to the γ Cru infrared magnitudes of Cohen & Barlow (1980). (b) Observed flux distributions of the WC8 and 9 stars. The 2–4 μm spectrophotometry of both objects is from Cohen & Vogel (1978). The photometry of Ve 2-45 is from Gehrz & Hackwell (1974); that of CRL 2104 below 4 μm is from Allen *et al.* (1977) and longward of 4 μm is from the AFGL catalogue (Price & Walker 1976). The dotted lines are eye fits to the *observed* flux distributions and do not correspond to the blackbody fits to the *dereddened* flux distributions discussed in the text.

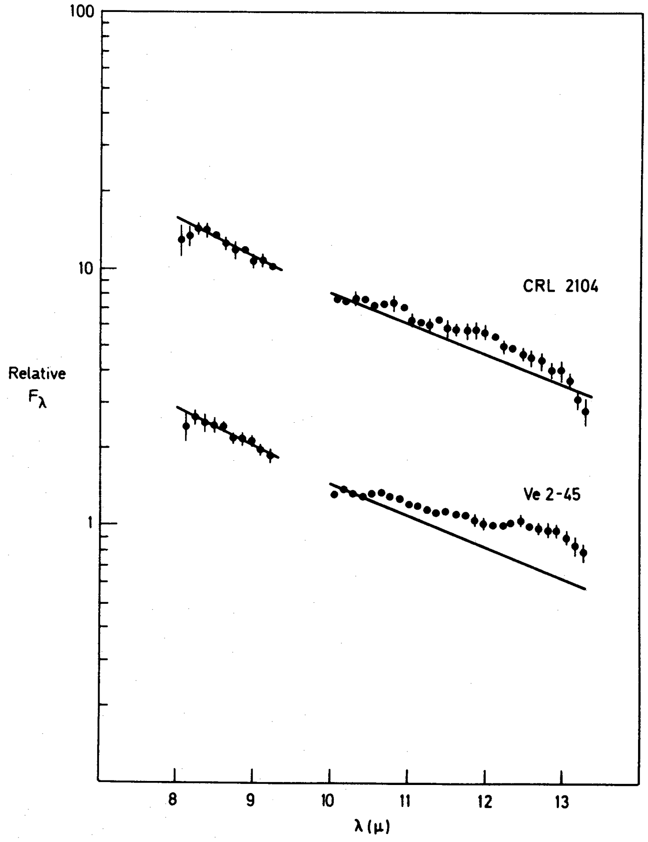


Figure 3. 8–13 μm spectra of Ve 2-45 and CRL 2104 after dereddening by $\tau_{10\,\mu\mathrm{m}} = 0.3$ and 0.6 respectively. The solid lines show 900 K blackbody slopes.

be attributed to SiC, although peaking at a longer wavelength than the excess seen in typical carbon stars (Fig. 3). The excess is not as prominent as implied by the broadband photometry of Ve 2-45 by Thomas *et al.* (1976). The value of $\tau_{10\,\mu\mathrm{m}} = 0.3$ for Ve 2-45 implies A_V(interstellar) = 4.2, compared to the interstellar A_V of 2.3 mag derived by Cohen *et al.* (1975) from the Na *D*-lines. Cohen & Kuhi (1977) derived $A_\mathrm{V} = 7.0$ mag interstellar plus circumstellar extinction towards Ve 2-45 so our derived interstellar extinction implies 2.8 mag circumstellar extinction. Our value of $\tau_{10\,\mu\mathrm{m}} = 0.6$ for CRL 2104 implies an interstellar A_V of 8.4 mag, consistent with the value of $A_\mathrm{V} = 9.3$ mag derived by Cohen & Kuhi (1976) for the interstellar extinction from the strength of the 6284 Å diffuse band. An interstellar A_V of 8.4 mag towards CRL 2104 implies a blackbody temperature of 900 K for the dereddened excess energy distribution. Since Cohen & Vogel derive $A_\mathrm{V} = 13$ mag interstellar plus circumstellar extinction towards CRL 2104, our derived interstellar extinction would imply a circumstellar extinction of 4.6 mag.

4 Infrared line emission

The [Ne II] line at 12.81 μm is marginally detected in both WC10 objects, and subsequent observations on the AAT in 1980 January have confirmed the presence of the line in He 2-113. The [Ne II] line intensities are:

CPD–56° 8032 : $2.1 \pm 0.6 \times 10^{-18}\ \mathrm{W\,cm^{-2}}$, 1978 July,

He 2-113 : $5.4 \pm 0.7 \times 10^{-18}\ \mathrm{W\,cm^{-2}}$, combined 1978 July and 1980 January.

These fluxes combined with the dereddened Hβ fluxes (8.4×10^{-19} W cm^{-2} for CPD–56° 8032 and 4.5×10^{-18} W cm^{-2} for He 2-113) may be used to derive the ionic abundance of Ne$^+$ relative to hydrogen in the nebulae around these objects (e.g. Petrosian 1970; Simpson 1975). We find

$$Ne^+/H^+ = 3.3 \times 10^{-4} \qquad \text{for CPD–56° 8032,}$$

$$Ne^+/H^+ = 1.56 \times 10^{-4} \qquad \text{for He 2-113.}$$

These values are 5 and 2.3 times the solar neon abundance, respectively, assuming that the effects of collisional de-excitation are negligible, i.e. that the electron density in the nebula does not greatly exceed 10^5 cm^{-3}. The majority of the neon is expected to be singly ionized in these low excitation objects; for stellar temperatures in the range 26 000 to 33 000 K, solutions of the equations of ionization equilibrium (e.g. Rank *et al.* 1978) indicate $Ne^+/Ne \gtrsim 0.95$. Similar overabundances of neon have been observed in some planetary nebulae (e.g. Gillett *et al.* 1973; Peimbert & Torres-Peimbert 1977; Aller 1978; Aitken *et al.* 1979b).

5 Discussion

Our optical spectrophotometry of CPD–56° 8032 yields continuum magnitudes of $B = 11.7$ and $V = 11.4$, which after dereddening give $V_0 = 9.55$ and $(B-V)_0 = -0.3$. Our optical spectrophotometry of He 2-113 does not extend beyond 5000 Å but, with the reasonable assumption that its intrinsic colours are the same as for CPD–56° 8032, the observed value of $B = 12.9$ yields a dereddened $V_0 = 9.0$. These magnitudes, in combination with the dereddened Hβ fluxes, may be used to derive effective temperatures for the stars by the Zanstra temperature method of Morton (1969). It is found that $\log (N_L/\pi F_V) = 10.51$ and 10.00 for He 2-113 and CPD–56° 8032 respectively, where N_L and F_V are the number of Lyman continuum photons and the V-band flux emitted by the stars per second. From Table 1 of Morton (1969) these values correspond to effective temperatures of 29 000 and 26 000 K respectively. The lower effective temperature of CPD–56° 8032 follows from the fact that it has three times less Hβ flux relative to the local continuum than does He 2-113. Since the spectra of the two stars are extremely similar, this differences may well be due to a loss of Lyman continuum photons either due to dust absorption or to escape, if the nebula surrounding CPD–56° 8032 is optically thin in the Lyman continuum. Support for the former hypothesis comes from a consideration of the stellar and infrared luminosities of the two objects.

Since their distances are unknown we will normalize to a distance of D kpc for each object. The stellar luminosity of He 2-113 following from its dereddened magnitude and Zanstra temperature is then $2.8 \times 10^3 D^2 L_\odot$. The observed infrared luminosity of He 2-113 between 1 and 20 μm is $1.3 \times 10^3 D^2 L_\odot$, whilst allowance for a minimum additional infrared luminosity longward of 20 μm obtained by fitting a blackbody to the 9.8 and 20 μm points and extrapolating, adds an extra $1.1 \times 10^3 D^2 L_\odot$, giving a total infrared luminosity of $2.4 \times 10^3 D^2 L_\odot$. Thus the stellar and infrared luminosity estimates are in fair agreement, indicating significant circumstellar dust absorption of the stellar continuum; with the possibility that dust may be competing efficiently with the gas for Lyman continuum photons. As a consequence, the effective temperature of 29 000 K derived for He 2-113 could be an underestimate. The case of CPD–56° 8032 is more pronounced. Its observed infrared luminosity between 1 and 20 μm is $2.2 \times 10^3 D^2 L_\odot$ and the minimum additional infrared luminosity emitted beyond 20 μm is $6.5 \times 10^2 D^2 L_\odot$. The stellar luminosity of CPD–56° 8032 which follows from its dereddened magnitude and an effective temperature of 26 600 K is $1.3 \times 10^3 D^2 L_\odot$, whilst for an effective temperature of 29 000 K its luminosity would be $1.7 \times 10^3 D^2 L_\odot$; still below its derived infrared luminosity. The infrared luminosity estimate can be reduced a little by assuming that it has a 2–13 μm spectrum with spectral peaks of strength similar to that of HD 44179 (Russell, Soifer & Willner 1978) but the resultant total infrared luminosity of $2.25 \times 10^3 D^2 L_\odot$ is still in excess of the luminosity corresponding to a 26000 or 29000 K star. Agreement is reached between the stellar and infrared luminosities of CPD–56° 8032 if it has an effective temperature of 33000 K, in which case 95 per cent of the Lyman continuum is absorbed by dust. If, as seems likely, He 2-113 has a similar effective temperature then 60 per cent of its total luminosity and 85 per cent of its Lyman continuum photons are absorbed by dust.

The galactic latitude of CPD–56° 8032 is −10°, and most of its observed extinction of $A_V = 1.85$ mag must be circumstellar, since the entire stellar luminosity is absorbed and re-emitted in the infrared by surrounding dust. He 2-113 is much closer to the galactic plane, with a latitude of +3°, so although its observed extinction of $A_V = 3.3$ mag is larger than that of CPD–56° 8032, a significant fraction is probably interstellar, consistent with the diffuse 4430 Å absorption band which is seen in its spectrum and which is not seen in the spectrum of CPD–56° 8032.

All objects in which the narrow features at 11.25 and 8.6 μm have been found are known to be subject to UV radiation, and it has been suggested (e.g. Allamandola & Norman 1978) that the features are due to UV excited fluorescent processes in grains or icy mantles on grains. In the two WC10 stars a large fraction of the stellar UV photons are absorbed by dust and it is possible to estimate the yield of infrared fluorescent photons per absorbed UV photon.

Taking the stellar model of Bradley & Morton (1969) with effective temperature 32 940 K and scaling to the dereddened V magnitudes of the two objects, we estimate the UV luminosity for wavelengths less than 0.35 μm as $N_{UV} = 4.8 \times 10^{47} D^2$ photon s^{-1} for CPD–56° 8032 and $N_{UV} = 8 \times 10^{47} D^2$ photon s^{-1} for He 2-113. Most of these photons are longward of the Lyman continuum. The infrared luminosity above background in a 0.2 μm band centred on the 11.25 μm feature is respectively $N_{11.25} = 1.2 \times 10^{47} D^2$ photon s^{-1} and $2.5 \times 10^{47} D^2$ photon s^{-1} and the fluorescent yield $N_{11.25}/N_{UV} = 0.25$ and 0.31. Since not all the UV photons are absorbed on grains, and it may be that the fluorescence arises from outside the ionized region, these values could be increased slightly and compare favourably with the value of 0.5 found for the feature in the 'Orion bar' (Aitken *et al.* 1979a).

The absolute magnitudes and evolutionary status of the WC10 stars are unknown. However, the presence of nebular forbidden lines in their optical and infrared spectra, the general similarity between their 8–13 μm spectra and those of some planetary nebulae, and the dissimilarity of their infrared spectra to those of the Population I WC8 and WC9 stars, lead us to concur with Webster & Glass (1974) that He 2-113 and CPD–56° 8032 are planetary nebulae having very cool central stars of the WC Wolf–Rayet sequence.

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