INFRARED (1.4 - 4.1μm) SPECTRA OF WOLF-RAYET STARS

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ABSTRACT

The spectra of a variety of Wolf-Rayet stars have been observed with ∿1% spectral resolution in the 1.4-4.1μm region using UKIRT. Strong lines due to ions of helium and carbon are observed and their relative strengths discussed. The He I singlet at 2.058μm is anomalously strong relative to other He I lines in WC stars and is responsible for the difference in the (H-K) colours of WN and WC stars. Emission line corrections to H, K and L magnitudes of different types are discussed. The Sanduleak 0 VI star ST 3 shows very strong C IV lines like the WC5 stars but not the strong He I.

We observe Wolf-Rayet stars in the infrared to study their mass loss. Apart from those WC stars surrounded by thermally emitting dust shells, many W-R stars show energy distributions in the infrared less steep than those of other hot stars owing to their extended mass loss envelopes. Most of our knowledge of mass loss rates comes from the interpretation of the infrared photometry using models for the mass outflows ranging from uniform circumstellar shells to those based on plausible density and velocity laws. Whatever the model, determination of the continuous energy distribution from infrared photometry requires allowance to be made for the flux carried in emission lines. To this end, and as part of the exploration of the infrared spectra of W-R stars, a variety of stars from the WN and WC sequences were scanned in the ranges 1.4-2.5μm and 3.0-4.1μm using circular variable filters having resolving powers $\lambda/\Delta\lambda \sim 100$ using the UKIRT.

As in the visible, the spectra of stars of the two sequences differ conspicuously. The 1.4-2.5μm spectra of a WN5 and a WC6 star are compared in Figure 1 together with the passbands of the H and K filters. Clearly, the significant difference in the (H-K) colours of WN and WC stars noted by Allen, Harvey & Swings (1972) is attributable to the emission line contribution to the K fluxes of the WC stars. Emission line corrections for these and other stars measured in this program are given in Table I.

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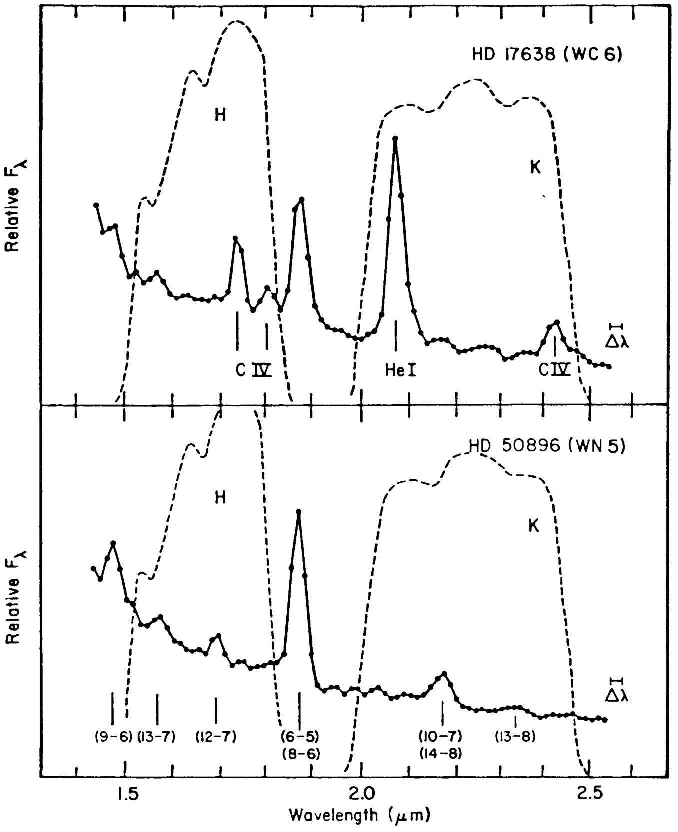

Figure 1. Comparison of 1.4 - 2.5μm spectra of WN5 and WC6 stars. The C IV transitions are (9-8) near 1.74μm and a bland of (10-9) and (13-11) near 2.42μm. C IV (14-11) and C III (10-8) fall near 1.8μm but there may be other contributors. The transitions marked on the WN5 spectrum are all due to He II.

TABLE I

EMISSION LINE CORRECTIONS

	WN3	WN5	WN8	WC5	WC6	WC8
ΔH	$0\overset{\mathrm{m}}{.}03$	$0\overset{\mathrm{m}}{.}07$	$0\overset{\mathrm{m}}{.}04$	$0\overset{\mathrm{m}}{.}15$	$0\overset{\mathrm{m}}{.}09$	$0\overset{\mathrm{m}}{.}08$
ΔK	0.02	0.04	0.04	0.42	0.34	0.30

The WN star shows most of the He II lines we would expect in this region. These lines are weaker in the WC spectrum, which is dominated by the He I 2s-2p singlet at 2.058μm and C IV. Observations of other WC5-WC8 stars by Williams et al. (1980) and Williams & Allen (1980) show a strong correlation between the strengths of the C IV

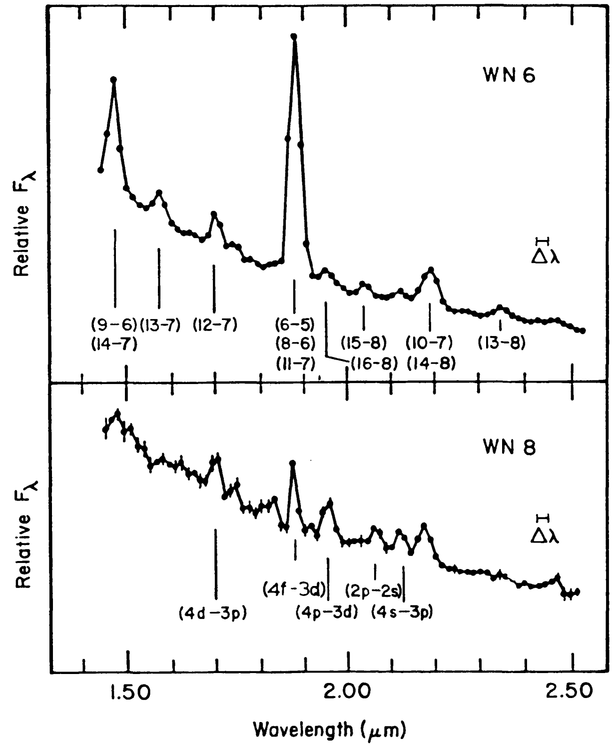

Figure 2. Excitation effects in WN stars HD 191765 and HD 177230. The He II are still dominant at WN6 while He I, mostly (4-3) triplets but also the (2s-2p) singlet, become important at WN8.

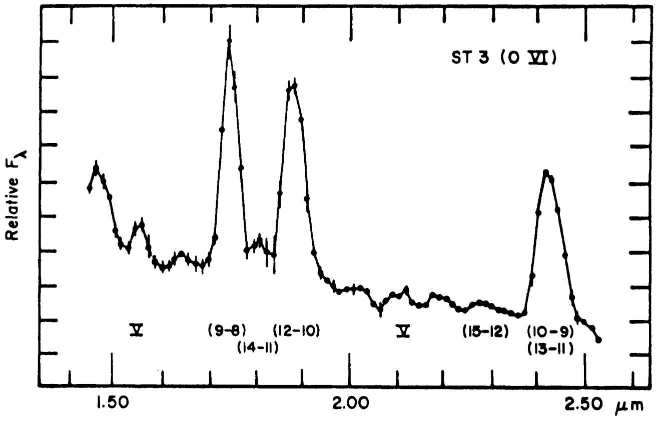

Figure 3. The O VI star Sanduleak 5 = ST 3 in the same region. The transitions marked are C IV although (12-10) must be masked by He II (6-5). We may be seeing C V (10-9) and (11-10) at 1.55 and 2.11 μm.

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lines and the He I 2.06μm line and excitation class. We expect the first from the visible spectra, while the second correlation is a consequence of a fundamental difference in the line formation mechanisms of the 2.06μm and other He I lines (which we have observed in WN8 and WC8 spectra only). The 2.06μm line shares its upper level with the λ584 resonance line so that its strength is a consequence of great optical depth in the resonance line and is determined by the (unobservable) far ultraviolet radiation field. Photoionization of hydrogen by the λ584 photons is not a severe limit on the build up of optical depth in this line in normal composition nebulae (Thompson & Tokunaga 1980) and may be insignificant in hydrogen poor Wolf-Rayet envelopes.

The He I line does not appear in the WN5 star, or in the WN6 star (Figure 2), and when it is seen in a WN8 star it has a comparable strength to other He I lines. Although He II is observed in the WN5 and WN6 spectra, the absence of the 2.06μm He I line cannot be due to ionization as its triplet counterpart at λ10830 has comparable strengths in WN and WC spectra (Kuhi 1966). The 2.06μm He I line is also not seen in the O VI Wolf-Rayet stars Sanduleak (1971) 4 and 5. Their spectra (Figure 3 for Sanduleak 5 = ST3) are dominated by the C IV lines which are even stronger than those in the WC5 spectra. The absence of the 2.06μm He I line, which attains its greatest strength at WC5, from the O VI stars is taken to demonstrate that these are not an extension of the WC sequence to higher excitation but that they form a separate sequence. The very different behaviour of the He I 2.06μm lines in the WN, WC and O VI stars is a diagnostic of their far ultraviolet radiation and must reflect fundamental differences in their structures.

The line at 3.28μm in the WC spectra in Figure 4 is of particular interest as it coincides in wavelength with the "unidentified dust" emission feature observed in a wide variety of high excitation sources. The identification with C IV is from hydrogenic levels, which have been used successfully for shorter wavelength transitions by Edlén (1956) and Kuhi (1966), and is supported by the line's being stronger at WC5 than at WC8. It is still stronger in the O VI star ST3. As a further check, we can go back and look for the (11-9) line expected near 1.395μm. Although this falls in an atmospheric water vapour band, it can be observed from Mauna Kea and the 1.4 micron spectra of the three stars shown in Figure 4 are presented in Figure 5. The line near 1.395μm is indeed stronger at WC5 than at WC8 and absent from WN6, effectively confirming the identifications.

The 3.3μm line falls on the edge of the L filter transmission, affecting L magnitudes of WC stars rather unpredictably, and photometry taken through the 3.8μm L' filter (which always includes the 4.05μm line) will be easier to convert to a continuum flux. The emission line corrections range from 0.06 mag (in WN6) to 0.18 mag (in the WC8 star).

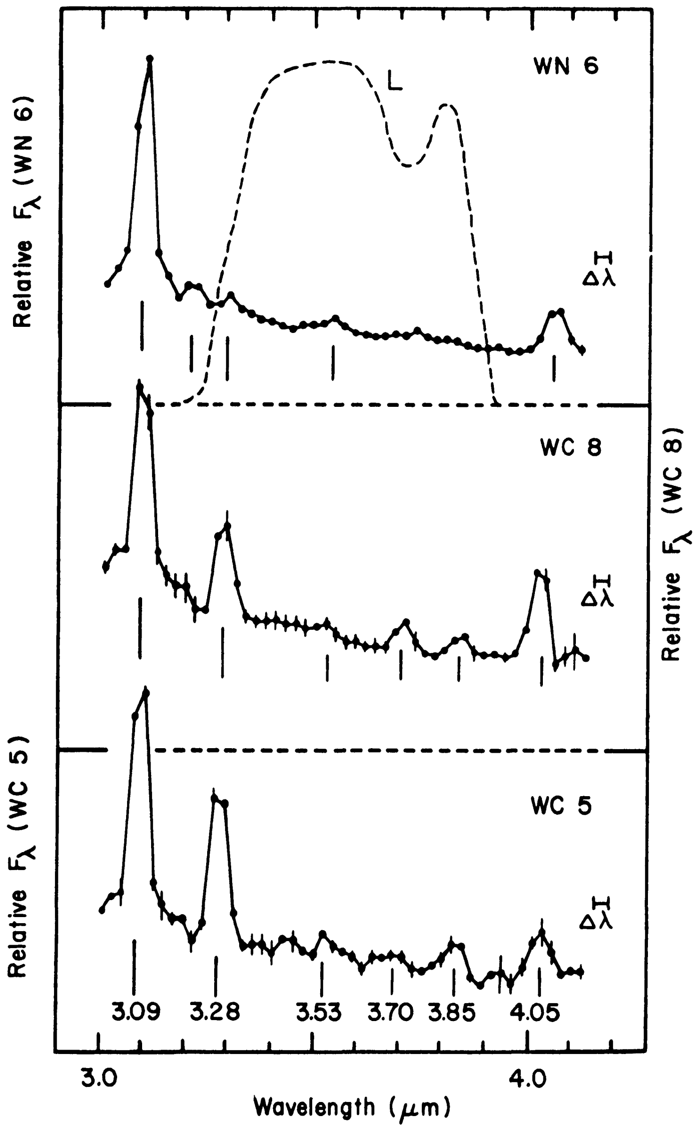

Figure 4. Comparison of 3-4.1μm spectra of WN and WC stars. The WN6 star shows He II (7-6) blended with (11-8) at 3.09μm, (10-8) at 4.05μm and (13-9) at 3.53μm. The WC stars show the He II lines more weakly, with C IV (11-10) at 3.28μm, (15-13) near 3.85μm with (14-12) perhaps contributing to the 3.09μm line. He I triplets 5d-4p at 3.7μm and a blend of 5g-4f and 5f-4d at 4.05μm appear in the WC8 star. The transmission of the 3.5μm L filter is shown for comparison.

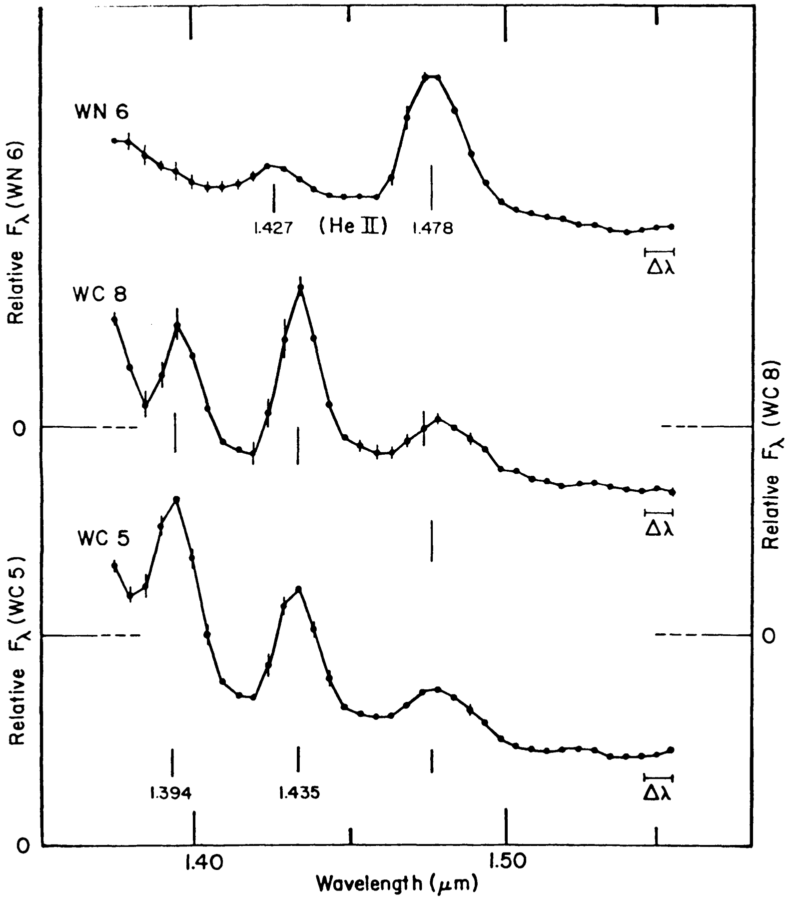

Figure 5. 1.38-1.55μm spectra of the same stars as in Figure 4. The spectral resolution is higher than that in Figure 1. The He II blend has comparable strength in all three spectra, the vertical scale of the WN spectrum being expanded to show He II (15-7) at 1.427μm. The line near 1.395μm is C IV (11-9). It is apparent that there is a line in the WC stars just shortward of the spectra; if real, it may be C III (7-6) which should fall near 1.37μm.

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