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1-μm spectroscopy of normal OB stars

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ABSTRACT

We have obtained spectra of 70 normal OB stars in the near-IR I (1-μm) band. The strongest features are those due to lines of the hydrogen Paschen series and neutral and ionized helium, which are, for the most part, in absorption. The information content in this spectral range is sufficient for only a rough classification of hot stars into 'early O', 'late O' and 'B' types. Curiously, the leading He I triplet line, He I λ1.0830 μm, is usually not detectable, although in a few stars it is in emission; its behaviour generally correlates with the leading helium singlet line, He I λ2.058 μm. These two features appear to be present in emission only in stars with extremes of mass loss or wind extension.

Key words: stars: atmospheres – stars: early-type – infrared: stars.

1 INTRODUCTION

It is only recently that advances in detectors and instrumentation have provided astronomers with opportunities for moderate-resolution spectroscopy ($R \geq 500$) in the near-IR *IJHK* bands. The principal motivations for working in this region are to extend the range of spectroscopic diagnostics available, and to enable heavily obscured stars to be studied (for example, the Galactic Centre cluster; Najarro et al. 1997). Most investigations of hot stars at these wavelengths have concentrated on objects showing *emission* lines, such as luminous blue variables (LBVs) (Allen, Jones & Hyland 1985; McGregor, Hyland & Hillier 1988), hot 'transition' stars (Morris et al. 1996) and Wolf–Rayet stars (Hillier, Jones & Hyland 1983; Howarth & Schmutz 1992; Bohannan & Crowther 1998). The incentive for near-IR spectroscopy of 'normal' OB stars is that their *absorption* lines may provide a classification scheme, and a frame of reference within which to interpret their more exotic brethren.

The detection of absorption lines in stellar spectra is more difficult than that of emission lines; one is dealing with weak features below the continuum, rather than often strong emission features above it. In addition to requiring at least moderate resolution, successful observations also require relatively high signal-to-noise (S/N) ratios; finally, there is always the problem of the Earth's atmospheric absorption, necessitating careful treatment of telluric features. In the present paper we offer a reconnaissance of I-band (0.98–1.10 μm) spectra of normal OB stars. In this we are following in the footsteps of the extensive and successful K-band classification work by Hanson, Conti & Rieke (1996) and Hanson, Howarth & Conti (1997); limited JH-band spectral observations have been given by Blum et al. (1997). The I region contains a number of features of potential interest from a classification viewpoint (e.g., the He I triplet at λ1.0830 μm), but is difficult to work in observationally, as both optical and infrared detectors typically have very poor response here. None the less, it can provide valuable information in heavily reddened systems if longer wavelengths are dominated by dust emission, or are otherwise contaminated (cf. Hanson et al. 1997).

2 DATA ACQUISITION AND REDUCTION

The data were obtained during the course of other programmes, primarily conducted with the Cassegrain spectrographs on telescopes of the Isaac Newton Group on La Palma: the Intermediate Dispersion Spectrograph (IDS) on the 2.5-m Isaac Newton Telescope, and ISIS on the 4.2-m William Herschel Telescope. The IDS was used with a 235-mm camera and 600I grating; a GEC chip was used as detector in 1990 August, and an EEV chip in 1992 July, each having 22-μm pixels and giving reciprocal dispersions of 1.6 Å pixel^{-1} ($R \simeq 3400$). A spectrum of HD 66811 (ζ Pup) was obtained for us in a service programme at the 3.9-m Anglo-Australian Telescope, with the RGO Spectrograph, 25-cm camera, and a $1024 \times 1024 \times 19$-μm Thomson CCD, closely matching the ING set-ups. The ISIS configuration (1995 July and August runs) was similar, but the 500-mm camera gave about twice the dispersion (and $R \simeq 5600$). More importantly, the thinned Tek chip used for the ISIS observations suffered fringing at the ~10 per cent level at 1 μm. This fringing does not fully flat-field out (even with flats which bracket the stellar spectra, with the telescope coordinates unchanged). However, the residual fringing is largely systematic, and can be reasonably well defined by (and corrected using) a global mean spectrum for a given run, with some manual 'tweaking'. The data were bias-corrected, flat-fielded, corrected for cosmic ray events, and optimally extracted with the Starlink FIGARO and ECHOMOP packages (Shortridge et al. 1997; Mills, Webb & Clayton 1997).

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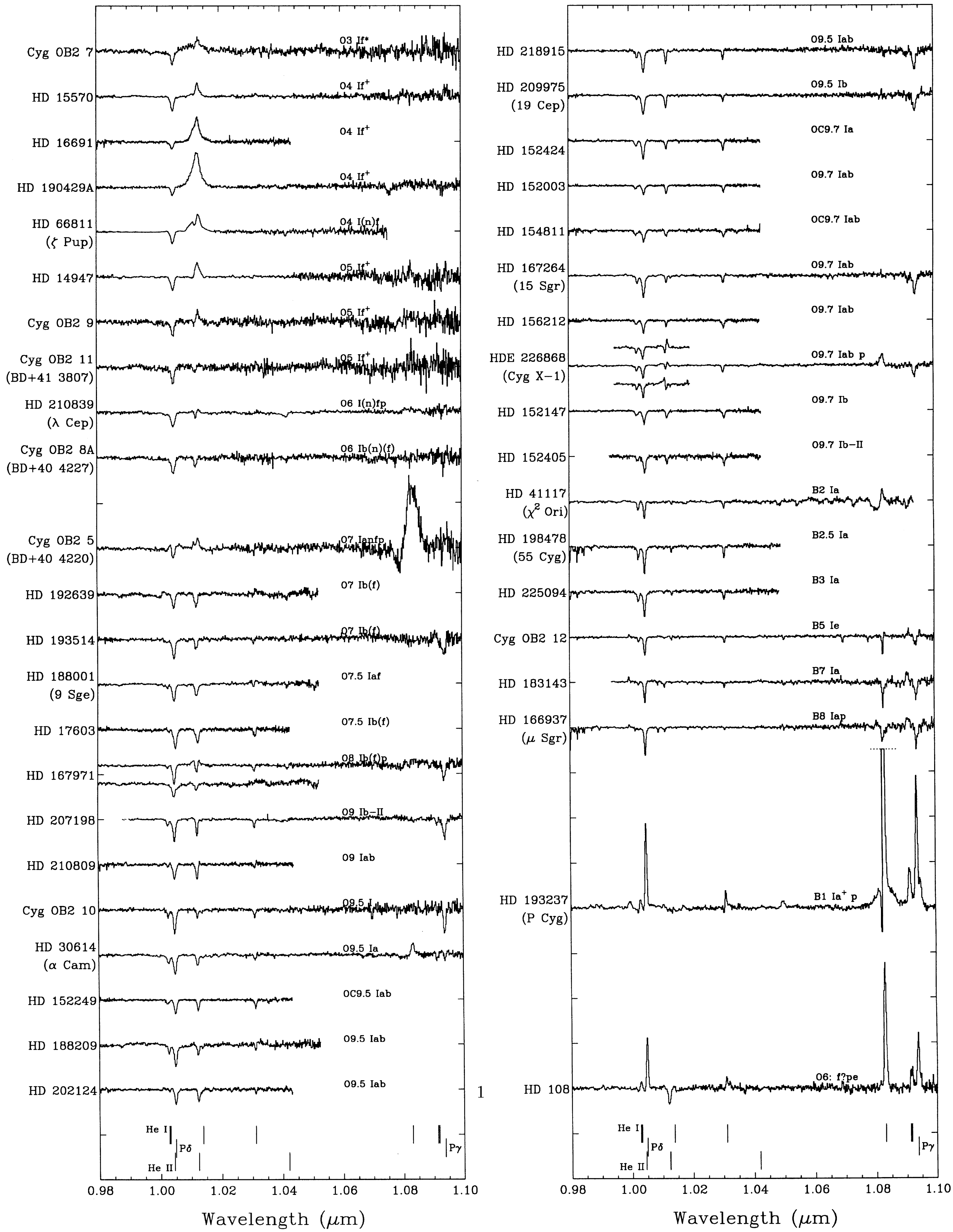

Cyg OB2 7
O3 If*
HD 15570
O4 If+
HD 16691
O4 If+
HD 190429A
O4 If+
HD 66811 (ζ Pup)
O4 I(n)f
HD 14947
O5 If+
Cyg OB2 9
O5 If+
Cyg OB2 11 (BD+41 3807)
O5 If+
HD 210839 (λ Cep)
O6 I(n)fp
Cyg OB2 8A (BD+40 4227)
O6 Ib(n)(f)
Cyg OB2 5 (BD+40 4220)
O7 Ianfp
HD 192639
O7 Ib(f)
HD 193514
O7 Ib(f)
HD 188001 (9 Sge)
O7.5 Iaf
HD 17603
O7.5 Ib(f)
HD 167971
O8 Ib(f)p
HD 207198
O9 Ib–II
HD 210809
O9 Iab
Cyg OB2 10
O9.5 I
HD 30614 (α Cam)
O9.5 Ia
HD 152249
OC9.5 Iab
HD 188209
O9.5 Iab
HD 202124
O9.5 Iab
1
He I
Pδ
He II
Pγ
0.98
1.00
1.02
1.04
1.06
1.08
1.10
Wavelength (μm)
HD 218915
O9.5 Iab
HD 209975 (19 Cep)
O9.5 Ib
HD 152424
OC9.7 Ia
HD 152003
O9.7 Iab
HD 154811
OC9.7 Iab
HD 167264 (15 Sgr)
O9.7 Iab
HD 156212
O9.7 Iab
HDE 226868 (Cyg X-1)
O9.7 Iab p
HD 152147
O9.7 Ib
HD 152405
O9.7 Ib–II
HD 41117 (χ2 Ori)
B2 Ia
HD 198478 (55 Cyg)
B2.5 Ia
HD 225094
B3 Ia
Cyg OB2 12
B5 Ie
HD 183143
B7 Ia
HD 166937 (μ Sgr)
B8 Iap
HD 193237 (P Cyg)
B1 Ia+ p
HD 108
O6: f?pe
He I
Pδ
He II
Pγ
0.98
1.00
1.02
1.04
1.06
1.08
1.10
Wavelength (μm)

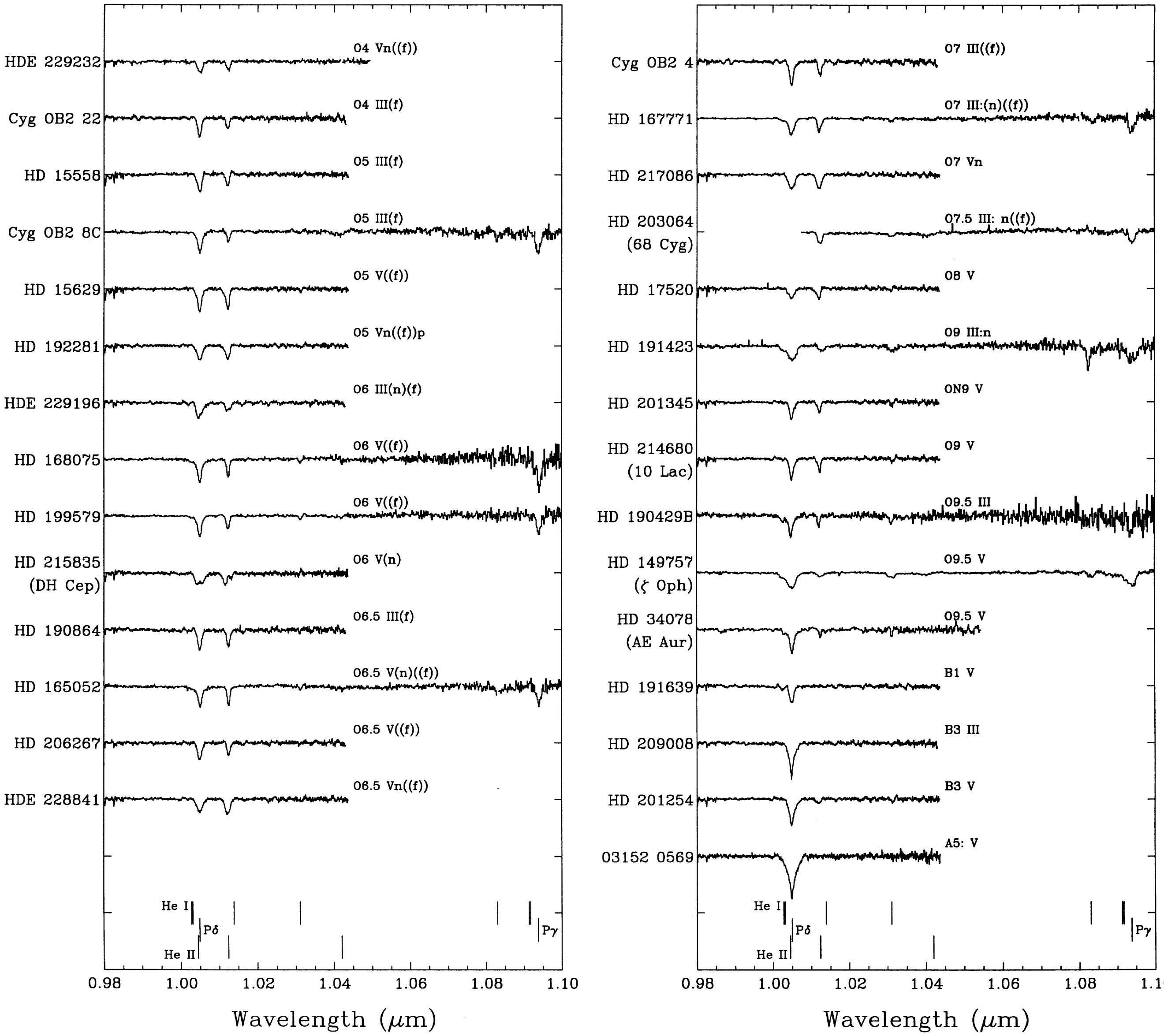

Figure 2. 1-μm spectra of early-type main-sequence stars; tickmarks on the *y*-axis are separated by 0.5 continuum units.

Telluric absorption is important only at the extreme wavelengths in our data. We constructed a telluric 'template' by averaging the spectra, aligned using cross-correlation to determine wavelength shifts, and editing out stellar features (which are easily separated at our resolution). The template was then scaled by line strength and divided into the individual spectra. This generally worked reasonably well (e.g., for HD 154811 which, at $\delta = -47°$, could not be observed from the WHT at a zenith distance of less than 75°).

The GEC CCD was too small to record simultaneously both the main helium lines of interest in this region (He II 1.0124 μm and He I 1.0830 μm), and the plummeting DQE of the larger chips in this region meant it was often difficult to obtain well-exposed spectra at all recorded wavelengths; these problems are reflected in some spectrum-to-spectrum variations in the wavelength coverage, as well as strongly wavelength-dependent S/N ratios. At λ1.0124 μm the S/N ratios are mostly in excess of 100; we obtained reasonable 1.0830-μm observations for only about half the sample, typically with S/N ratios of 10–30.

We obtained multiple spectra for a number of stars; in two cases, discussed in Section 3.4, there was clear evidence of spectroscopic variability. All other spectra were averaged, weighted by detected photons, and are shown in Figs 1 (supergiants) and 2 (giants and main-sequence stars). Equivalent-width measurements are given in Tables 1 and 2. In a few cases, comparison can be made with earlier work by Jaschek et al. (1994); agreement is generally quite satisfactory.

3 SUMMARY OF FEATURES

The overall impression from the spectra shown in Figs 1 and 2 is that

Figure 1. Rectified 1-μm spectra of early-type supergiants; tickmarks on the *y*-axis are separated by 0.5 continuum units. Two spectra of HD 167971 are plotted to illustrate line-profile variability, and the mean of four spectra of HDE 226868 (the optical counterpart of Cyg X-1) is shown together with illustrations of the two extreme morphologies of He II λ1.0124 μm. The He I λ1.0830-μm line in P Cyg's spectrum reaches a normalized intensity of 6.4.

a few hydrogen and helium lines are present which are, for the most part, in absorption. The Pδ and Pγ lines change little in strength or appearance among the illustrated normal spectral types, except for the expected increase in strength in the B-type main-sequence stars, and there are no significant metal-line features apparent. These factors mitigate against a precise classification scheme for early-type stars in this region.

He II λ1.0124 μm (5–4) is present in all the O-star spectra, but is undetectable in the B stars. [A nearby weak feature ($W_\lambda \simeq 0.2$ Å), most easily seen in the sharp-lined early-B supergiants, is He I λ1.0138 μm.] It is consistently in absorption in the main-sequence stars, but in the earliest O-type supergiants is found in emission, somewhat analogous to Wolf–Rayet stars (e.g. Crowther & Smith 1996), but weaker (see also Conti et al. 1995). For these supergiants, the dispersion in λ1.1024-μm line strength at given spectral type is noteworthy; part of this dispersion may be a consequence of poor correction for the fringing noted in Section 2, but this cannot explain the differences between the O5 If$^+$ stars Cyg OB2#9, #11, and HD 14947, for example.

He I λ1.0311 μm is detectable in absorption, beginning at O7 in luminous stars and extending cooler to at least the mid-B supergiants. Main-sequence O stars of types O7: and later show weak absorption in this line, but it is weak or absent at our spectral resolution and S/N ratio in the few B-type main-sequence stars we observed. The He I $\lambda\lambda$1.0027, 1.0031-μm blend shows broadly similar behaviour, but the He I λ1.0914-μm blend is detected only in the B supergiants, together with the peculiar star HD 108; remarkably, it is always in *emission* in our sample.

The important He I transition at λ1.0830 μm (2^3S–2^3P^o) lies in this spectral region; while it shows rather diverse behaviour, it is *undetectable* in many of our spectra of normal O stars! It is, however, present as an absorption line in the exceptionally rapidly

Table 1. Equivalent-width measurements for major features in supergiant spectra; errors are in each case propagated from the dispersion in the local continuum. Ellipsis dots indicate no measurable feature, and dashes indicate no spectral data. The 'Obs.' column indicates the instrumentation and epoch of observation: A1 = AAT (1991); I0, I2 = INT (1990, 1992); W = WHT (1995). The 'Ref.' column gives the source of the spectral type: W71–76 = Walborn (1971, 1972, 1973a, 1976); C73 = Walborn 1973b; Wp = Walborn (personal communication); MT = Massey & Thompson 1991; MCW = Morgan, Code & Whitford (1955).

Star	Sp.	Ref.	Obs.	He I 10029	H (Pδ) 10049	He II 10124	He I 10311	He I 10830	H (Pγ) 10938
Cyg OB2 7	O3 If*	C73	I0, W	...	+1.35 ± 0.29	−6.45 ± 0.61	...	...	...
HD 15570	O4 If$^+$	W72	I0, W	...	+1.83 ± 0.07	−2.40 ± 0.20	...	...	...
HD 16691	O4 If$^+$	W73	W	...	+1.02 ± 0.08	−5.81 ± 0.10	...	—	—
HD 190429A	O4 If$^+$	W73	I2	...	+0.99 ± 0.17	−13.7 ± 0.34	...	−0.93 ± 0.99	+1.00 ± 0.54
HD 66811	O4 I(n)f	W72	A1	...	+1.64 ± 0.05	−5.83 ± 0.08	...	—	—
HD 14947	O5 If$^+$	W73	I0, W	...	+1.83 ± 0.08	−3.12 ± 0.11	...	...	...
Cyg OB2 9	O5 If$^+$	C73	I0, W	...	+1.62 ± 0.31	−1.54 ± 0.39	...	...	...
Cyg OB2 11	O5 If$^+$	C73	I0,W	...	+1.56 ± 0.27	+0.49 ± 0.26	...	...	...
HD 210839	O6 I(n)fp	W73	I0, I2	...	+2.18 ± 0.14	−0.31 ± 0.16	...	...	...
Cyg OB2 8A	O6 Ib(n)(f)	C73	I0	...	+2.20 ± 0.20	+0.78 ± 0.18	...	...	...
HD 108	O6: f?pe	W72	I0	−0.69 ± 0.16	−3.90 ± 0.17	+1.86 ± 0.20	−1.19 ± 0.20	−12.1 ± 0.48	−5.10 ± 0.48
HD 192639	O7 Ib(f)	W72	I0	...	+1.76 ± 0.16	+1.58 ± 0.17	...	—	—
HD 193514	O7 Ib(f)	W72	I2	...	+2.28 ± 0.17	+0.95 ± 0.13	+0.31 ± 0.11	...	+2.75 ± 0.54
Cyg OB2 5	O7 Ianfp	C73	I0	...	−0.26 ± 0.23	−1.56 ± 0.20	...	−26.9 ± 2.0	...
HD 188001	O7.5 Iaf	W72	I0, W	+0.22 ± 0.05	+1.97 ± 0.07	+1.26 ± 0.07	+0.30 ± 0.11	—	—
HD 17603	O7.5 Ib(f)	W73	W	...	+2.51 ± 0.07	+1.69 ± 0.08	+0.23 ± 0.08	—	—
HD 167971	O8 Ib(f)p	W72	I0	+0.17 ± 0.08	+1.67 ± 0.25	−0.58–+0.55	+0.40 ± 0.09	...	+1.44 ± 0.38
HD 207198	O9 Ib–II	W76	I2	+0.51 ± 0.06	+2.42 ± 0.08	+1.13 ± 0.06	+0.51 ± 0.07	...	+2.01 ± 0.21
HD 210809	O9 Iab	W76	W	+0.20 ± 0.06	+1.96 ± 0.08	+1.41 ± 0.07	+0.19 ± 0.06	—	—
HD 30614	O9.5 Ia	W76	I0	+0.62 ± 0.08	+2.08 ± 0.10	+0.94 ± 0.09	+0.36 ± 0.08	−1.72 ± 0.29	+0.42 ± 0.21
HD 152249	OC9.5 Iab	W76	W	+0.53 ± 0.10	+1.67 ± 0.12	+0.98 ± 0.11	+0.67 ± 0.11	—	—
HD 188209	O9.5 Iab	W76	I0	+0.59 ± 0.14	+2.25 ± 0.19	+0.84 ± 0.16	+0.50 ± 0.16	—	—
HD 202124	O9.5 Iab	W76	W	+0.11 ± 0.07	+1.59 ± 0.10	+1.18 ± 0.10	+0.23 ± 0.07	—	—
HD 209975	O9.5 Ib	W76	I2, W	+0.27 ± 0.04	+2.36 ± 0.06	+1.01 ± 0.05	+0.32 ± 0.04	...	+1.97 ± 0.26
HD 218915	O9.5Iab	W76	I2	+0.58 ± 0.09	+2.58 ± 0.12	+0.79 ± 0.10	+0.52 ± 0.12	...	+1.86 ± 0.30
Cyg OB2 10	O9.5 I	MT	I2, W	+0.40 ± 0.11	+2.38 ± 0.16	+0.46 ± 0.12	+0.49 ± 0.15	...	+2.29 ± 0.53
HD 152424	OC9.7 Ia	W76	W	+0.62 ± 0.06	+2.02 ± 0.08	+0.71 ± 0.07	+0.78 ± 0.06	—	—
HD 152003	O9.7 Iab	W76	W	+0.41 ± 0.06	+1.07 ± 0.07	+0.72 ± 0.05	+0.56 ± 0.06	—	—
HD 154811	OC9.7 Iab	W76	W	+0.57 ± 0.14	+1.35 ± 0.16	+0.51 ± 0.13	+0.48 ± 0.12	—	—
HD 156212	O9.7Iab	W76	W5	+0.48 ± 0.05	+1.39 ± 0.12	+0.43 ± 0.09	+0.76 ± 0.12	—	—
HD 167264	O9.7 Iab	W73	I0, I2	+0.66 ± 0.07	+2.47 ± 0.08	+0.47 ± 0.06	+0.49 ± 0.06	...	+2.16 ± 0.29
HDE 226868	O9.7 Iab p	W73	I2	+0.61 ± 0.04	+1.43 ± 0.05	−0.17 ± −0.31	+0.52 ± 0.03	−1.71 ± 0.18	+1.07 ± 0.13
HD 152147	O9.7 Ib	W76	W	+0.60 ± 0.06	+1.53 ± 0.06	+0.67 ± 0.05	+0.69 ± 0.06	—	—
HD 152405	O9.7 Ib–II	W76	W	+0.40 ± 0.09	+1.96 ± 0.12	+0.50 ± 0.09	+0.63 ± 0.10	—	—
P Cyg	B1 Ia$^+$ p	Wp	I0	−0.52 ± 0.25	−6.27 ± 0.25	...	−1.34 ± 0.21	−50.3 ± 0.75	−15.6 ± 0.48
HD 41117	B2 Ia	W76	W	+0.68 ± 0.09	+1.34 ± 0.11	...	+0.36 ± 0.09	+1.11 ± 0.42	—
HD 198478	B2.5 Ia	W71	I2	+0.98 ± 0.12	+2.56 ± 0.13	...	+0.61 ± 0.10	—	—
HDE 225094	B3 Ia	MCW	I2	+0.94 ± 0.12	+2.56 ± 0.13	...	+0.58 ± 0.10	—	—
Cyg OB2 12	B5 Ie	MT	I0, I2	+0.36 ± 0.05	+1.55 ± 0.07	...	+0.39 ± 0.05	+0.60 ± 0.19	+0.67 ± 0.18
HD 183143	B7 Ia	MCW	I2	+0.16 ± 0.05	+1.61 ± 0.07	...	+0.25 ± 0.05	+1.71 ± 0.24	+1.64 ± 0.22
HD 166937	B8 Iap	MCW	I2	...	+2.27 ± 0.07	...	+0.09 ± 0.04	+1.53 ± 0.32	+1.76 ± 0.32

Table 2. Equivalent-width measurements for major features in giant and main-sequence spectra; errors are propagated from the dispersion in the local continua. Ellipsis dots indicate no measurable feature, and dashes indicate no spectral data. The 'Obs.' column indicates the instrumentation and epoch of observation: I0, I2 = INT (1990, 1992); W5, W7 = WHT (1995, 1997). The 'Ref.' column gives the source of the spectral type: MT = Massey & Thompson (1991); C71 = Conti & Alschuler (1971); FTW = Feast, Thackeray & Wesselink (1957); W72–82 = Walborn (1972, 1973a, 1976, 1982); C73 = Walborn (1973b); MCW = Morgan, Code & Whitford (1955).

Star	Sp.	Ref.	Obs	H (Pδ) 10049	He II 10124	He I 10311	He I 10830	H (Pγ) 10938
Cyg OB2 22	O4 III(f)	MT	W5	+1.87 ± 0.09	+0.83 ± 0.07	...	—	—
HDE 229232	O4 Vn((f))	W73	W7	+1.44 ± 0.06	+0.79 ± 0.05	...	—	—
HD 15558	O5 III(f)	W72	W5	+2.10 ± 0.08	+1.24 ± 0.07	...	—	—
Cyg OB2 8C	O5 III(f)	C73	I2, W5	+2.58 ± 0.13	+0.93 ± 0.10	...	+0.34 ± 0.38	+2.16 ± 0.48
HD 15629	O5 V((f))	W72	W5	+2.77 ± 0.08	+2.08 ± 0.08	+0.12 ± 0.06	—	—
HD 192281	O5 Vn((f))p	W72	W5	+2.14 ± 0.10	+1.54 ± 0.08	+0.07 ± 0.05	—	—
HDE 229196	O6 III(n)(f)	W73	W5	+2.23 ± 0.07	+1.14 ± 0.06	...	—	—
HD 168075	O6 V((f))	W82	I2	+3.02 ± 0.21	+1.40 ± 0.16	+0.24 ± 0.12	...	+4.30 ± 0.71
HD 199579	O6 V((f))	W73	I2, W5	+2.56 ± 0.13	+1.22 ± 0.11	+0.30 ± 0.08	...	+1.70 ± 0.33
HD 215835	O6 V(n)	W73	W5	+2.41 ± 0.11	+1.66 ± 0.10	...	—	—
HD 190864	O6.5 III(f)	W72	W5	+2.20 ± 0.11	+1.53 ± 0.10	...	—	—
HD 165052	O6.5 V(n)((f))	W73	I2	+2.44 ± 0.13	+1.42 ± 0.09	+0.20 ± 0.07	...	+1.88 ± 0.37
HD 206267	O6.5 V((f))	W73	W5	+2.05 ± 0.09	+1.18 ± 0.07	...	—	—
HDE 228841	O6.5 Vn((f))	W73	W5	+1.99 ± 0.09	+2.02 ± 0.07	...	—	—
HD 167771	O7 III: (n)((f))	W72	I0, I2	+2.45 ± 0.08	+1.34 ± 0.07	+0.20 ± 0.06	+0.37 ± 0.28	+1.93 ± 0.33
Cyg OB2 4	O7 III ((f))	C73	W5	+2.77 ± 0.11	+1.21 ± 0.10	+0.12 ± 0.06	—	—
HD 217086	O7 Vn	W73	W5	+2.46 ± 0.07	+1.99 ± 0.07	...	—	—
HD 203064	O7.5 III: n((f))	W73	I2	—	+1.38 ± 0.10	+0.48 ± 0.09	...	+1.72 ± 0.30
HD 17520	O8 V	W73	W5	+1.45 ± 0.10	+1.12 ± 0.10	+0.11 ± 0.05	—	—
HD 191423	O9 III: n	W73	I2	+3.47 ± 0.16	+0.75 ± 0.16	+0.71 ± 0.15	+1.63 ± 0.47	+2.37 ± 0.58
HD 201345	ON9 V	W76	W5	+1.84 ± 0.08	+0.94 ± 0.07	+0.31 ± 0.06	—	—
HD 214680	O9 V	W72	W5	+2.30 ± 0.09	+1.05 ± 0.08	+0.22 ± 0.05	—	—
HD 190429B	O9.5 III	C71	I2	+2.81 ± 0.19	+0.66 ± 0.13	+0.47 ± 0.19	...	+1.65 ± 0.82
HD 34078	O9.5 V	W72	I0	+3.85 ± 0.15	+0.49 ± 0.09	+0.21 ± 0.15	—	—
HD 149757	O9.5 V	MCW	I2	+4.08 ± 0.11	+0.57 ± 0.09	+0.77 ± 0.09	+0.62 ± 0.19	+2.85 ± 0.23
HD 191639	B1 V	MCW	W5	+1.93 ± 0.08	+0.00 ± 0.06	...	—	—
HD 209008	B3 III	MCW	W5	+4.15 ± 0.09	...	...	—	—
HD 201254	B3 V	FTW	W5	+3.95 ± 0.11	+0.54 ± 0.10	+0.19 ± 0.05	—	—
GSC 03152 0569	A5: V	–	W5	+8.10 ± 0.25	...	...	—	—

rotating late-O near-main-sequence stars HD 191423 (O9 III:n; $v_e \sin i = 436$ km s^{-1} according to Howarth et al. 1997) and HD 149757 (ζ Oph, O9.5 V; 372 km s^{-1}), and in the late-O and B-type supergiants, with a variety of morphologies. The normal supergiants HD 30614 (α Cam, O9.5 Ia) and HD 41117 (χ^2 Ori, B2 Ia) show P Cygni profiles, as do the peculiar stars Cyg OB2#5 (O7 Ianfp), Cyg OB2#12 (B5 Ie) and P Cyg. It appears to be a pure emission line in HD 108 and HDE 226868, and shows no emission above the continuum in the supergiants HD 183143 (B7 Ia) and HD 166937 (B8 Iap). As anticipated by Blum et al. (1997), the behaviour of this triplet is therefore not well correlated with spectral type.

3.1 An attempt at classification

The paucity of lines in this region at our S/N ratio and resolution, together with a lack of strong trends in most features, precludes a detailed classification scheme. However, keeping in mind what we know of the behaviour of the helium lines in blue-region classification spectra, we can roughly classify the observed morphologically normal stars using just the He II λ1.0124-μm line and He I λλ1.003, 1.031-μm features, as follows.

(i) 'Luminous early O': He II in emission, He I absent (corresponding to O3–O5 I).

(ii) 'Early main-sequence O': He II absorption, He I undetectable (earlier than ~O5).

(iii) 'Late O': He II *and* He I absorption. There is little to distinguish supergiants and main-sequence stars reliably, although the He I lines appear somewhat stronger in the supergiants, which also tend to have narrower lines (e.g., the λλ1.003- and 1.012-μm lines are well resolved in all our supergiant spectra). This is partly because the supergiants are all *relatively* slow rotators ($v_e \sin i \approx 100$ km s^{-1}; cf. Conti & Ebbets 1977, Howarth et al. 1997), but the distinction appears to hold even for the slowly rotating main-sequence stars (e.g., HD 214680), and is presumably a consequence of differences in pressure broadening.

(iv) B supergiants: He I absorption, He II absent. We do not have enough observational material for substantial comment on the B-type main-sequence stars, but, in our spectra, only Pδ is observed.

While this is not very satisfactory from the perspective of accurate classification, spectra such as ours could provide an initial categorization of hot stars in optically obscured regions. It might be noted that while A-type stars would show strong Paschen lines in absorption, He I should certainly be absent (see, for example, the shorter wavelength observations by Andrillat, Jaschek & Jaschek 1995; also the spectrum of GSC 03152 0569 in Fig. 2).

3.2 Correlation with lines in the *K* band

It is of interest to compare the behaviour of the leading IR He I triplet at λ1.0830 μm with the λ2.058-μm ($2^1S-2^1P^o$) singlet. For the latter *K*-band line there are the extensive illustrations and measurements of a larger sample of OB stars from Hanson et al. (1996). We can summarize our results as follows.

(i) In most OB stars *neither* line is present!

(ii) Some hot stars have absorption at the singlet line but no feature detectable in the triplet; this is probably due in part to lower S/N ratio in this part of the *I* band (where we also have less extensive data).

(iii) In the few stars with emission or P Cygni profiles in the triplet, a similar profile is found in the singlet. A notable exception is HD 30614 (α Cam), which shows the triplet in emission while the singlet is in absorption. We have no explanation for this anomaly, as there is no established binary nature for this star; possibly it is a non-LTE effect (cf. Murdoch, Drew & Anderson 1994). Detailed models would be required to check this, but we note that the strength of λ2.058 μm is expected to be sensitively dependent on the optical depth in the λ584-Å He I resonance line, with which it shares an upper level (2^1P).

It is also interesting to compare He II λ1.0124 μm (5–4) with He II λ2.189 μm (10–7) in the *K* band (from Hanson et al. 1996). For most O stars, both lines are in absorption. For those luminous early O stars with He II λ1.0124 μm in emission (Fig. 1), two also show He II λ2.189 μm in emission (HD 16691 and 190429A); the other stars (HD 66811, HD 14947, HD 15570 and Cyg OB2#11) have the *K*-band line in absorption. Given the nature of the He II transitions, (5–4) versus (10–7), it is reasonable to expect that the former line will come into emission before the latter one. Conti et al. (1995) have noted the similarity of HD 16691 and 190429A to WN stars of relatively late type, given the He II λ2.189-μm emission in each. We see an analogous behaviour with the He II λ1.0124-μm feature, a transition into emission in the hottest and most luminous Of stars.

3.3 Correlation with lines in the *J* and *H* bands

Our sample includes three of the four O-type stars in the sparse *H*-band survey conducted by Blum et al. (1997): HD 190429A, 199579 and 190864. The *H*-band spectra show the upper Brackett series to be undetectable, while our observations (and Blum et al.'s) show the lower Paschen lines in absorption. At B spectral types the Brackett series also comes into absorption, as expected.

3.4 Notes on individual stars

3.4.1 HD 108

The *I*-band spectrum is surprisingly similar to that of P Cyg (with the exception of the presence of He II λ1.0124 μm in absorption in HD 108 – as would be expected, given its O-type classification). He I λ1.0830-μm emission is very strong in both stars; this line originates in a very extended region around P Cyg and, by analogy, we suggest that HD 108 shares this ('circumstellar'?) characteristic.

3.4.2 HD 167971

This is a multiple system, including the eclipsing pair MY Ser (cf. Leitherer et al. 1987, Howarth et al. 1997). Our two spectra show significant variability in He II λ1.0124 μm (Fig. 1).

3.4.3 HD 190429

The A and B components are separated by 1.96 arcsec (ESA 1997). The spectra we present here were obtained in exceptionally good (0.5-arcsec) seeing, and there appears to be no significant 'cross-talk' between them (for example, the 1.0124-μm line is very strongly in emission in HD 190429A, but there is no trace of this feature in the B-component spectrum).

The 1.0830-μm line was also observed by Blum et al. (1997), who report a distinct P Cygni profile dominated by a broad emission component; they also find that Pβ has a weak P Cygni feature, while Pγ is weakly in absorption. Our spectrum shows a clearly blue-shifted 1.0830-μm absorption ($W_\lambda = +1.4 \pm 0.5$ Å), whose displacement corresponds extremely well to the star's terminal velocity (1880 km s^{-1}; Howarth et al. 1997). The associated emission is very weak in our spectrum, however – not more than about 3 per cent above continuum (cf. ~6 per cent in Blum et al.'s spectrum). This is probably just within the margin of combined rectification errors, although our spectrum gives well-defined continuum, and was obtained with a thick chip which suffered no fringing. None the less, since Blum et al.'s spectrum probably refers to the combined light of the A and B components (they used a 5-arcsec slit in 2–4 arcsec seeing) – so that one might expect the A-component emission to be *diluted* in their spectrum – variability is a distinct possibility.

3.4.4 HD 193237 (P Cyg)

The He I λ1.0830-μm line is a P Cygni feature; the very strong emission gives rise to a broad pedestal of electron-scattered line photons.

3.4.5 HDE 201254

The possible weak He II λ1.0124-μm absorption visible in Fig. 1 is probably an artefact of the fringing noted in Section 2, as is the suggestion of P Cygni structure in He I λ1.0311 μm.

3.4.6 HDE 226868

HDE 226868 is the optical counterpart of Cyg X-1. We have four spectra, which show considerable variability in He II λ1.0124 μm (Fig. 1); this variability is probably directly related to the phase-dependent changes in He II λ4686 discussed by Gies & Bolton (1986).

3.4.7 HDE 229232/GSC 03152 0569

With a spectral type of O4 Vn((f)), HDE 229232 (BD+38 4070) is earliest bright main-sequence star in the northern-hemisphere summer sky. At the time of writing, the coordinates listed in the CDS data base for this star are those of GSC 03152 0569. We observed this target and found its spectrum to be completely inconsistent with an early O type (Fig. 2); a blue-region spectrum (4050–4850 Å, unfortunately omitting the Ca K line) indicates an ~A5 V classification.

Subsequent blue and 1-μm spectra of the nearby object GSC 03152 0289, kindly obtained at our request by D. L. Pollacco, confirm that it is this star which is HDE 229232. The coordinates of both GSC stars are in agreement with the approximate position recorded in the HD catalogue (Cannon 1925), but 03152 0289 is somewhat brighter, and its spectrum is in better accord with the HD classification of 'B' (a common classification for stars now considered O type). Thus the correct coordinates of HDE 229232 are $20^h\ 23^m\ 59\overset{s}{.}2$, $+39°\ 06'\ 14''$ (J2000).

3.4.8 *Cyg OB2#5*

He I λ1.0830 μm shows an exceptionally well-developed P Cygni profile. Cyg OB2#5 (BD+40 4220, V729 Cyg) is a close interacting binary (Conti & Bohannan 1976; see also Contreras et al. 1997), in which the formation of He I λ1.0830 μm could reasonably be tied to the presence of circumstellar material, together with the huge mass-loss rate (see below); this is supported by the anomalous He II 1.0124 μm emission.

The bluemost point of the steepest part of the absorption component in λ1.0830μm is a good indicator of the terminal velocity for such a strong line (Howarth & Schmutz 1992), and yields $v_\infty = 1500$ km s^{-1}, with an uncertainty not exceeding ~10 per cent. This is the first reliable estimate of v_∞ for OB2#5; combined with multifrequency radio observations of free–free emission (Contreras et al. 1996), it implies $\dot{M} = (3.7 \pm 1.3) \times 10^{-5}$ M$_\odot$ yr^{-1}.

3.4.9 *Cyg OB2#12*

In addition to a more-or-less normal absorption-line spectrum, Cyg OB2#12 is unusual in showing a number of weak emission lines (observed wavelengths λλ0.9998, 1.0914 and 1.0952 μm); He I λ1.0830 μm has a P Cygni profile with a weak but clear emission component. These features reproduce well across all available spectra, including those taken with thick chips. The exceptional luminosity of this star (cf. Massey & Thompson 1991), and HD 166937, should not go unnoticed.

4 CONCLUSIONS

Observations of the few hydrogen and neutral and ionized helium lines in the *I*-band spectra of hot stars can give us only a very rough indication of the spectral types. Nevertheless, such data could be useful in conjunction with longer wavelength near-IR spectroscopy to help elucidate the nature of these objects. We call attention to the behaviour of the He II λ1.0124 μm (5–4) in the hottest Of type stars: a transition into emission analogous to, but more sensitive than, He II λ2.189 μm (10–7). The leading triplet He I line, λ1.0830μm, is not usually present, a behaviour analogous to the leading singlet feature at λ2.058μm. In a few stars this line does show up weakly in absorption, with a P Cygni profile, or strongly in emission.

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