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An atlas of 2.4 to 4.1 μm ISO/SWS spectra of early-type stars*,**

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Abstract. We present an atlas of spectra of O- and B-type stars, obtained with the Short Wavelength Spectrometer (SWS) during the Post-Helium program of the Infrared Space Observatory (ISO). This program is aimed at extending the Morgan & Keenan classification scheme into the near-infrared. Later type stars will be discussed in a separate publication. The observations consist of 57 SWS Post-Helium spectra from 2.4 to 4.1 μm, supplemented with 10 spectra acquired during the nominal mission with a similar observational setting. For B-type stars, this sample provides ample spectral coverage in terms of subtype and luminosity class. For O-type stars, the ISO sample is coarse and therefore is complemented with 8 UKIRT L₀-band observations. In terms of the presence of diagnostic lines, the L₀-band is likely the most promising of the near-infrared atmospheric windows for the study of the physical properties of B stars. Specifically, this wavelength interval contains the Br, Pγ, and other Pfund lines which are probes of spectral type, luminosity class and mass loss. Here, we present simple empirical methods based on the lines present in the 2.4 to 4.1 μm interval that allow the determination of:

i) the spectral type of B dwarfs and giants to within two subtypes;

ii) the luminosity class of B stars to within two classes;

iii) the mass-loss rate of O stars and B supergiants to within 0.25 dex.

Key words. line: identification – atlases – stars: early-type – stars: fundamental parameters – infrared: stars

1. Introduction

The advance of infrared-detector technology since the eighties has opened new perspectives for the study of early-type stars. Investigation of the early phases of their evolution especially benefits from infrared (IR) observations. The birth places of massive stars are identified with Ultra-Compact HII regions (UCHII). In such regions, the stars are still embedded in material left over from the star formation process and are obscured at optical and ultraviolet wavelengths. In the K-band (ranging from 2.0 to 2.4 μm) dust optical depths τ of a few occur, while in the H-band (ranging from 1.5 to 1.8 μm) τ is typically of order ten. At shorter wavelengths, the dust extinction becomes too high to observe the embedded stars. The IR emission of the warm dust cocoon covering the newly formed massive stars in UCHII regions peaks typically at about 100 μm. At wavelengths longwards of 5−10 μm, the thermal emission of the dust dominates the photospheric flux, and can be as much as 4 orders of magnitude above the stellar free-free continuum at 100 μm (Churchwell 1991).

Reliable values for the luminosities, temperatures and mass-loss rates of the embedded massive stars are essential as they allow us to trace the very early phases of their evolution of which little is known. Furthermore, these parameters control the photo-dissociation and ionisation of the molecular gas, the evaporation of the dust, and affect the morphology of the UCHII region.

The development of quantitative diagnostics based on IR spectral data requires, as a first step, homogeneous observations of a large set of both normal and peculiar non-embedded early-type stars, that have been studied in detail at optical and ultraviolet wavelengths where OB-type stars exhibit many spectral lines. Such stars may be used to calibrate quantitative methods based on IR spectroscopy alone. Calibration work has

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** The appendix is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/384/473
Table 1. The 12 O-type stars and one Wolf-Rayet star observed during the ISO/SWS Post-Helium mission, supplemented with 7 O stars observed with CGS4/UKIRT. The spectrum averaged signal-to-noise ratio ($S/N$) is listed in the last column.

<table>
<thead>
<tr>
<th>Star Name</th>
<th>Name</th>
<th>Spectral Type</th>
<th>Spect. Type Reference$^a$</th>
<th>ISO Observation Number</th>
<th>Instrument</th>
<th>S/N</th>
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<td>W72</td>
<td>89 300 401</td>
<td>UKIRT</td>
<td>220</td>
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<td>O5V(f)</td>
<td>W72</td>
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<td>UKIRT</td>
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<tr>
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</tr>
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<td>W72</td>
<td>90 000 801</td>
<td>ISO/PHe 70</td>
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</tr>
<tr>
<td>HD 24912</td>
<td>ζ Per</td>
<td>O7.5III((f))</td>
<td>W73</td>
<td>90 000 601</td>
<td>ISO/PHe 20</td>
<td></td>
</tr>
<tr>
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<td>QZ Sge</td>
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<td>ISO/PHe 10</td>
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<tr>
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<td>λ Ori A</td>
<td>O8III((f))</td>
<td>W72</td>
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<td>ISO/PHe 25</td>
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<tr>
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<td>O9V((n))</td>
<td>W72</td>
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<td>ISO/PHe 15</td>
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</tr>
<tr>
<td>HD 37043</td>
<td>o Ori</td>
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<td>W72</td>
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<td>W72</td>
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<td>HD 38666</td>
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<tr>
<td>HD 209975</td>
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<td>ISO/PHe 45</td>
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<td>WR 147</td>
<td></td>
<td>O9</td>
<td>S96</td>
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<td>ISO/PHe 35</td>
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already been carried out in other near-infrared wavelength ranges, in the J-band by e.g. Wallace et al. (2000), in the H-band by e.g. Meyer et al. (1998) and Hanson et al. (1998), and in the K-band Hanson et al. (1996). The “Post-Helium program” conducted with the Short Wavelength Spectrometer (SWS) on board the Infrared Space Observatory (ISO) is intended to provide such a data set. This mission started after helium boil-off in April 1998 and made use of the ability of the detectors of SWS to acquire observations in band 1 [2.4–4.1 μm] during the slow warming of the satellite (see also Sect. 2.1). The band 1 of ISO SWS ranges from 2.4 to 4.1 μm, and is, like the K-band, positioned favourably in the narrow window in which newly born stars can be observed directly. This wavelength region contains important diagnostic hydrogen lines of the Brackett ($Br\alpha$, $Br\beta$), Pfund ($Pf\gamma$), and Humphreys series.

In this paper, we present and study 75 spectra of early-type stars, 67 [2.4–4.1 μm] ISO/SWS spectra and 8 [3.5–4.1 μm] spectra observed with the United Kingdom Infrared Telescope (UKIRT). This sample includes OB, Be, and Luminous Blue Variable (LBV) stars. We discuss line trends as a function of spectral type, following a strategy similar to the one adopted by Hanson et al. (1996) for the K-band. Simple empirical methods are employed to derive the spectral type and/or luminosity class. These methods may also be applied if only ground-based $L^*$-band spectra are available (which cover a smaller wavelength range).

The paper is organised as follows: in Sect. 2 we discuss the data acquisition and reduction techniques; Sect. 2.3 comprises a catalogue of good quality spectra; Sect. 3 provides the line identifications. Line trends and methods to classify OB-type stars are presented in Sect. 4, while Sect. 5 describes the spectra of B stars with emission lines. The results are summarised in the final section. The equivalent-width measurements are listed in the Appendix.

2. Observations

2.1. The ISO/SWS sample

The ISO spectra were obtained with ISO/SWS (SWS, de Graauw et al. 1996; ISO, Kessler et al. 1996). After helium boil-off of the ISO satellite on 8 April 1998, the near-infrared band 1 [2.4–4.1 μm] of SWS equipped with InSb detectors could still be operated as the temperature at the focal plane increased only slowly. Between 13 April and 10 May, spectra of nearly 250 bright stars were acquired for a stellar classification program. Referred to as “Post-Helium observations”, this program aims at extending the MK classification scheme into the near-infrared.

In this paper we present the subset of O- and B-type stars observed during the Post-Helium phase. These observations were executed using a dedicated engineering observation mode, the so-called Post-Helium observation template. All the spectra obtained during the Post-Helium program, including later spectral types, as well as details about the data acquisition will be published in a separate publication (Vandenbussche et al. in prep). Along with these Post-Helium spectra, we include ten spectra of O and B stars measured during the nominal mission using Astronomical Observation Template 1 speed 4 [AOT01].
Table 2. The 30 B-type stars observed during the ISO/SWS Post-Helium mission, supplemented with 3 stars from the ISO/SWS nominal mission and 1 star observed with CGS4/UKIRT.

<table>
<thead>
<tr>
<th>Star Name</th>
<th>Name</th>
<th>Spectral Type</th>
<th>Spect. Type Reference*</th>
<th>ISO Observation Number</th>
<th>Instrument</th>
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<td>M55</td>
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<td>HD 93030</td>
<td>θ Car</td>
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<td>B62</td>
<td>25 900 905</td>
<td>ISO/Nom</td>
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<td>HD 198781</td>
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<td>ISO/PHe</td>
</tr>
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<td>HD 207793</td>
<td>HR 7134</td>
<td>B0.5III</td>
<td>M55</td>
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<td>HD 185859</td>
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<td>M55</td>
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<td>ISO/PHe</td>
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<tr>
<td>HD 116658</td>
<td>α Vir</td>
<td>B1V</td>
<td>M55</td>
<td>25 302 001</td>
<td>ISO/Nom</td>
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<tr>
<td>HD 208218</td>
<td>R1III</td>
<td>M55</td>
<td>88 701 101</td>
<td>ISO/PHe</td>
<td>7</td>
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<tr>
<td>HD 190066</td>
<td>β lab</td>
<td>M55</td>
<td>88 101 401</td>
<td>ISO/PHe</td>
<td>15</td>
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<tr>
<td>HD 158926</td>
<td>Λ Sco</td>
<td>B1.5IV</td>
<td>H69</td>
<td>49 101 016</td>
<td>ISO/Nom</td>
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<tr>
<td>HD 52089</td>
<td>ε Cma</td>
<td>B1.5II</td>
<td>W90</td>
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<td>ISO/PHe</td>
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<td>HD 194279</td>
<td>V2118 Cyg</td>
<td>B1.5Ia</td>
<td>L92</td>
<td>88 201 301</td>
<td>ISO/PHe</td>
</tr>
<tr>
<td>HD 193924</td>
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<td>L75</td>
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<td>ISO/PHe</td>
</tr>
<tr>
<td>HD 206165</td>
<td>9 Cep</td>
<td>B2 II</td>
<td>L68</td>
<td>88 300 301</td>
<td>ISO/PHe</td>
</tr>
<tr>
<td>HD 198478</td>
<td>55 Cyg</td>
<td>B2.5Ia</td>
<td>L68</td>
<td>88 100 501</td>
<td>ISO/PHe</td>
</tr>
<tr>
<td>HD 160762</td>
<td>δ Her</td>
<td>B3 V</td>
<td>J53</td>
<td>89 900 101</td>
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<tr>
<td>HD 207330</td>
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<td>ISO/PHe</td>
</tr>
<tr>
<td>HD 15371</td>
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<td>H69</td>
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<td>ISO/PHe</td>
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<tr>
<td>HD 184930</td>
<td>ϵ Aqu</td>
<td>B5III</td>
<td>L68</td>
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<tr>
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<td>HD 58350</td>
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<td>B5Ia</td>
<td>W90</td>
<td>90 702 301</td>
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<tr>
<td>HIC 101364</td>
<td>Cyg OB2 12</td>
<td>B5Ia</td>
<td>M91</td>
<td>90 300 901</td>
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<td>HD 203245</td>
<td>HR 8161</td>
<td>B6V</td>
<td>L68</td>
<td>88 701 401</td>
<td>ISO/PHe</td>
</tr>
<tr>
<td>HD 155763</td>
<td>ζ Dra</td>
<td>B6III</td>
<td>L68</td>
<td>89 900 201</td>
<td>ISO/PHe</td>
</tr>
<tr>
<td>HD 209952</td>
<td>α Gru</td>
<td>B7 IV</td>
<td>H69</td>
<td>88 500 701</td>
<td>ISO/PHe</td>
</tr>
<tr>
<td>HD 183143</td>
<td>HT Sge</td>
<td>B7Ia</td>
<td>M55</td>
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<tr>
<td>HD 14228</td>
<td>φ Eri</td>
<td>B8V-IV</td>
<td>H69</td>
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<td>ISO/PHe</td>
</tr>
<tr>
<td>HD 207971</td>
<td>γ Gru</td>
<td>B8III</td>
<td>H82</td>
<td>88 500 901</td>
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<tr>
<td>HD 208501</td>
<td>13 Cep</td>
<td>B8B</td>
<td>L92</td>
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</table>


Both observation templates use the same scanning strategy, SWS takes a full continuous spectrum over four preset overlapping sub-bands. These are defined in Table 4. The integration time per target is fixed, therefore the S/N ratio mainly depends on the brightness of the source.

Combining the nominal and Post-Helium program AOT01 speed 4 observations, we collected 69 ISO/SWS spectra. However, two targets (HD 147165 and HD 203245) were clearly off-pointed and will therefore not be discussed. We split the remaining 67 stars into two subgroups: the O- and B-type stars, and the B stars with emission-line spectra. Spectra over 2.4-4.1 μm for the majority of these stars are presented for the first time. For comparison with Of supergiants, we have included the Wolf-Rayet star WR 147 (Van der Hucht et al. 1996) in the first subgroup. The second subgroup includes 18 Be and 3 Luminous Blue Variable (LBV) stars (see Humphreys & Davidson 1994 for a review). Spectra of AG Car and P Cyg have been presented by Lamers et al. (1996a,b). The 45 OB stars are listed in Tables 1 and 2 together with 8 OB stars observed with UKIRT; the 21 B stars with emission lines are given in Table 3.

Each table provides the HD number and stellar name; the spectral type and luminosity class; the ISO/SWS observation number and a label indicating whether the observation was done during the nominal or Post-Helium program, quoted by the acronym ISO/Nom and ISO/PHe, respectively. The last column provides a spectrum averaged value of the signal-to-noise ratio (S/N) of the observation (see Sect. 2.1.1). On average the S/N is relatively low for the O- and early B-type stars: only 5 out of 22 stars...
Table 3. The 14 B stars with emission lines observed in the ISO/SWS Post-Helium mission supplemented with 7 stars observed during the ISO/SWS nominal mission.

<table>
<thead>
<tr>
<th>Star Name</th>
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<td>P93</td>
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</tr>
<tr>
<td>HD 50013</td>
<td>B2IV-Ve</td>
<td>H69</td>
<td>90 000 101</td>
<td>ISO/PHe</td>
<td>140</td>
</tr>
<tr>
<td>HD 50123</td>
<td>B2IV-Ve</td>
<td>S</td>
<td>88 601 901</td>
<td>ISO/PHe</td>
<td>75</td>
</tr>
<tr>
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<td>B2Vpe</td>
<td>L68</td>
<td>90 800 901</td>
<td>ISO/PHe</td>
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</tr>
<tr>
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<td>ISO/PHe</td>
<td>20</td>
</tr>
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<td>H69</td>
<td>90 000 101</td>
<td>ISO/PHe</td>
<td>140</td>
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<td>90 702 101</td>
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<td>20</td>
</tr>
<tr>
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<td>S</td>
<td>88 601 901</td>
<td>ISO/Phe</td>
<td>75</td>
</tr>
<tr>
<td>HD 198183</td>
<td>B6Ve</td>
<td>L68</td>
<td>90 900 801</td>
<td>ISO/Phe</td>
<td>35</td>
</tr>
<tr>
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<td>L68</td>
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<td>ISO/Phe</td>
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<tr>
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<td>L68</td>
<td>33 504 002</td>
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</tr>
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<td>B2pe</td>
<td>H75</td>
<td>22 400 153</td>
<td>ISO/Nom</td>
<td>80</td>
</tr>
<tr>
<td>HD 93308</td>
<td>Bpe</td>
<td>H75</td>
<td>07 100 250</td>
<td>ISO/Nom</td>
<td>170</td>
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</table>


Table 4. The spectral resolution $R$ and wavelength coverage of the four sub-bands, for a detailed technical specification see de Grauw et al. (1996).

<table>
<thead>
<tr>
<th>preset sub-band</th>
<th>$R = \Delta \lambda/\lambda$</th>
<th>wavelength coverage (µm)</th>
</tr>
</thead>
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<tr>
<td>band 1a</td>
<td>1870-2110</td>
<td>2.38-2.60</td>
</tr>
<tr>
<td>band 1b</td>
<td>1470-1750</td>
<td>2.60-3.02</td>
</tr>
<tr>
<td>band 1d</td>
<td>1750-2150</td>
<td>3.02-3.52</td>
</tr>
<tr>
<td>band 1e</td>
<td>1290-1540</td>
<td>3.52-4.08</td>
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</table>

of spectral type earlier than B2 have a $S/N \geq 60$; for the later type stars the situation is reversed, i.e. only 5 out of 23 have $S/N \leq 60$. This tendency is explained by the lack of relatively nearby bright O and early-B stars compared to later B stars. For the B stars with emission lines, the $S/N$ of the continuum is not that important as the emission lines are very prominent in most of the spectra.

The 34 B stars provide a fairly dense coverage of B spectral types, but this is not the case with the 12 O stars. Moreover, because of the relatively low $S/N$ of our observations, we could not detect lines in any of the five O V stars. Lines are detected, however, in supergiant O stars. We obtained $L'$-band UKIRT observations in order to improve the coverage of O spectral types. These are discussed in Sect. 2.2. The subgroup of B stars with emission-line spectra shows a diversity in the way their circumstellar material is distributed: 18 Be stars with discs and/or shells and 3 LBV stars (ζ Carinae, AG Carinae and P Cygni) with dense stellar winds.

2.1.1. ISO/SWS data reduction

The data acquired during the nominal mission were calibrated in the SWS Interactive Analysis environment with the calibration files as in Off-Line Processing Version 10.0. The Post-Helium data required special care as changes in the characteristics of the instrument arose when the temperature increased. A time-dependent calibration was derived, based on reference observations in each orbital revolution of the satellite. This accounts for changes in wavelength calibration and photometric sensitivity as a function of wavelength. Fortunately, the spectral resolution did not change and the dark current and noise remained fairly similar, as the signal recorded with closed instrument shutter is still dominated by the amplifier offsets. The exact sources of instrumental drifts cannot be fully disentangled but a reliable empirical calibration could be derived. The Post-Helium calibration, which is described in detail in Vandenburg (2000), results in a data quality that is comparable to that during the nominal mission. To illustrate this: P Cyg was observed both during the nominal and Post-helium missions, the spectra show a continuum level variation of 4% and a line width variation of 5%.

All the spectra were processed from the Auto-Analysis Result stage using the SWS Interactive Analysis (IA$^3$) programs. First, the behaviour of the individual detectors was checked. Second, the two independent spectral scans were compared. Discrepancies were treated when
The 3.5 to 4.12 μm region of the spectra of O-type stars obtained with CGS4/UKIRT. All O stars in this sample show Brα emission in the core.

their cause was clearly established (jumps, glitches, residual tilt in the slope of the Post-Helium spectra). The adopted spectral resolution per sub-band is very similar to the $R$ values given in Sect. 2.1, but not strictly identical, as the final rebinning is based on on-board measurements (see Lorente et al. 1998; Hony et al. 2000).

### 2.2. The CGS4/UKIRT sample

The UKIRT spectra were obtained on the second half of the night of 23 December 2000 (UT) using the Cooled Grating Spectrometer 4 (CGS4; Mountain et al. 1990). We obtained $L'$-band (3.5–4.1 μm) spectra of 8 stars with spectral types ranging from O4 to B0. The 40 l/mm grating was used in first order with the 300 mm focal length camera and the 0.6′′ wide slit, giving a nominal resolution of 0.0025 μm ($R \approx 1500$). The array was stepped to provide 2 data points per resolution element. Signal-to-noise ratios of 70 to 200 were achieved on the continua of the target hot stars. The four O V stars, with subtypes O4, O5, O7, and O9.5 significantly improve the coverage of spectral types. Three O7 to O9 giants were also observed, as well as one B0 supergiant.

For data reduction, we used the Starlink Figaro package. Spectra were ratioed by those of dwarf A and F stars observed on the same night at similar airmasses as the hot stars, corrected for the approximate effective temperatures of the stars by multiplying by a blackbody function. Wavelength calibration was achieved using the second order spectrum of an argon arc lamp. The spectra shown here have been slightly smoothed, and have a resolution of 0.0031 μm ($R \approx 1200$).

### 2.3. Atlas

We present the normalised ISO/SWS spectra of O and B stars with $S/N$ greater than 30 from 2.6 to 3.35 μm and from 3.65 to 4.08 μm in Figs. 2 to 4. We do not display the band 1a (from 2.4 to 2.6 μm) because the $S/N$ of this sub-band, containing the higher Pfund series and for two stars only a probable Si IV line, is significantly lower than for the others. The spectra from 3.35 to 3.65 μm do not show any detectable lines. Figure 1 displays the $L'$-band spectra obtained with CGS4/UKIRT. Figures 5 and 6 display the full ISO/SWS band 1 spectra of all Be and Luminous Blue Variables stars in our sample. Line identifications are provided in each of the figures.
3. Identification and measurement of spectral lines

In this section, we give an overview of the lines observed in the 2.4 to 4.1 μm region and review how we measured line strengths and widths. The investigated spectral range is dominated by lines of hydrogen and helium. We made a special effort to identify lines of other elements, resulting in the detection of only one silicon emission line in two late O supergiants and a few lines of oxygen, magnesium and iron, in the sample of B stars with emission lines.

3.1. Overview of lines in the 2.4 to 4.1 μm region

Hydrogen lines of three different series are present in this wavelength region: the two leading lines of the Brackett series Brα λ4.0523 (wavelength in μm) and Brβ λ2.6259;
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Fig. 3. The 2.6 to 3.35 μm region of the spectra of B5- to B9-type stars contains the Brβ line at 2.6259 μm and some lines of the Pfund series. Helium lines are no longer present.

- The Pfund series from Pfγ (3.7406) to Pf(22→5) (3.4036), and the higher members of the Humphreys series starting from transition Hu(14→6) (4.0209). The lower members of each series, such as Brι, Brβ and Pfγ, are expected to be particularly important diagnostic lines.

- Lines of ionised helium are identified in three O supergiant stars. The (7→6) transition at 3.0917 is expected to be the strongest Heii line in the H, K and L′-bands. A second strong Heii line, (9→7) at 3.8260, is detected in the spectrum of the early-O supergiant HD 190429 and possibly in HD 188001 and HD 30614. It is likely that Heii (10→8), (11→8) and (12→8) are present in the spectrum of HD 190429 based on a comparison with WR 147, but as these lines are located in the wings of the much stronger Bro, Heii (7→6) and Brβ lines, respectively, we cannot provide a positive identification.

- The neutral helium line that is expected to be the strongest is Hei (5d→4f) at 4.0490. Unfortunately, this line is blended with Brα. The second strongest Hei line in band 1 is the (5f→4d) transition at 4.0377. This line
Fig. 4. The 3.65 to 4.08 μm region of the spectra of O9- to B9-type stars contains the Br\textalpha\ line at λ 4.0523 μm and some of the Humphreys series lines. He\textsc{i} lines are present down to spectral type B3 and are identified with arrows in the top of the figure. The OB supergiants show Br\textalpha\ emission down to B7/8.

is observed in absorption in stars from spectral type O9.5 down to B2.5 and in emission in Be stars of similar spectral type. Of comparable strength are He\textsc{i} (5d–4p) 3.7036 and (6f–4d) 2.6192. One would also expect, He\textsc{i} (6g–4f) 2.6241, but this line is blended with Br\textbeta\ and could not be detected.

We found an emission line at λ 2.4275 in the two good quality spectra of the late-O supergiants HD 30614 and HD 195592, the most likely identification being Si\textsc{iv}(4f–4d). A few permitted O\textsc{i} as well as Fe\textsc{ii} and likely Mg\textsc{ii} lines could be identified in several Be stars and/or LBVs. Fe\textsc{ii} (4s–4p) at λ 3.0813, λ 3.5423 and λ 3.9378 is present in all three LBVs as well as in a few Be stars. Mg\textsc{ii} (5p–4p) at λ 2.4048 and λ 2.4131 is possibly identified in all three LBVs. These identifications are consistent with the K-band spectra for the same stars, see
Fig. 5. The full band 1 spectra from 2.40 to 4.08 μm of B0e to B2.5e stars contain hydrogen lines of the Brackett, Pfund and Humphreys series. In most of the spectra, the only He\(_I\) line present is at 4.0377. A few stars also show some O\(_I\) lines.

Hanson et al. (1996). Finally, four neutral oxygen lines are seen in early Be stars as well as in two LBVs: O\(_I\) (4p–4s) at λ2.764 and λ2.893, O\(_I\) (5s–4p) at λ3.662 and O\(_I\) (4d–4p) at λ3.098. All identified lines are listed in Table 5.

A few forbidden lines are also observed in the spectra of LBV’s and WR. We did not investigate those lines here, a listing of those can be found in Lamers et al. (1996b) and Morris et al. (2000).

### 3.2. Of supergiants and WR 147

The spectra of the two Of supergiants in our sample are plotted in Fig. 7 together with the spectrum of the Wolf-Rayet star WR 147. The ISO/SWS spectrum of WR147 has been analysed in detail by Morris et al. (2000). The line strengths in the Of spectra are significantly less than in the spectrum of WR 147, which is mainly a result of the
higher density of the wind of the Wolf-Rayet star. Line ratios such as Br/\beta/Br\alpha and Pf\alpha/Br\alpha are roughly similar for both the Of stars and the WN8h, indicating the primary dependence of the line on mass flux $\dot{M}/4\pi R_w^2$. However, the He\,\textsc{ii} (7–6)/Br\alpha line in HD 190429 is stronger by a factor of three compared to WR 147, indicating that this
Table 5. Lines identified in the [2.4–4.1] μm region.

<table>
<thead>
<tr>
<th>λ_vac (μm)</th>
<th>Element</th>
<th>Configuration</th>
<th>λ_vac (μm)</th>
<th>Element</th>
<th>Configuration</th>
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<td>6–22</td>
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Fig. 7. Comparison of H I and He II lines between early Of-type supergiants and WR 147 in the 2.4 to 4.1 μm region. Line ratios such as Br γ/Br α and Pf γ/Br α are roughly similar; however He II (7–6) λ3.092/Br α in HD 190429 is stronger by a factor of three compared to WR 147, being consistent with the higher temperature of the O4If star (see Conti & Underhill 1988).

O4 star is significantly hotter. The higher temperature of the O4 If stars is also implied by the absence of He I lines. A distinction between these types seems possible on the basis of overall line strength of the spectra (cf. Morris et al. 1997), though further investigation of WR spectral characteristics in the near-infrared is still needed to more firmly establish Of/WN differences (as in the K-band study of “transition” spectra by Morris et al. 1996) and connections.

Concerning the O7.5 If star, the Brackett lines are weaker and narrower than in the O4 If star indicating a lower mass-loss rate. Again, we do not detect He I lines;
Fig. 8. The equivalent widths of Brα (top panel) and Brβ (bottom panel) for normal B-type stars. Stars of luminosity classes Ia-II are denoted by square symbols; class III by circles, and classes IV-V by crosses. The dotted lines indicate where the lines revert from absorption ($W_{eq} > 0$) to emission ($W_{eq} < 0$). For both lines, the B dwarfs and sub-giants show a gradual increase in absorption strength towards later spectral type. This can not be seen clearly in this figure, however the linear fit parameters of this trend are given in Table 6. In B supergiants and bright giants the line strength remains about constant, albeit with a large scatter.

the narrow feature at the position of the HeⅡ lines might be spurious. All other features between 3.4 and 4.0 μm are due to noise.

3.3. Equivalent width

For consistency in the measurements of equivalent widths, we first rebin the UKIRT spectra to the resolution of ISO/SWS. We then define the continuum regions after removing all the spectral sections containing identifiable lines. A normalisation function of the form $A_0 + A_1 \times X + A_2 \times X^2$ is fitted to each of the 4 sub-bands. The $S/N$ is computed as being the inverse of the standard deviation on the normalised continuum. The line parameters, equivalent width ($EW$) and full width at half maximum ($FWHM$) are measured on the normalised spectra using the ISO Spectral Analysis Package. The errors on those measurements are dominated by the uncertainty in the position of the continuum, which is ~5% (Decin et al. 2000). For unblended lines, the tool MOMENT is used as it gives statistical parameters without making any assumptions on the shape of the profile.

The signal-to-noise ratio and the spectral resolution of the ISO/SWS sample may vary over the spectrum (up to 50%), as well as within a sub-band. This is largely intrinsic to the instrument setting and depends little on the difference in flux over wavelengths; the $S/N$ varies inversely to the spectral resolution.

The $EW$s of the lines used in our analysis (see Sect. 4) are presented in the Appendix. Concerning the O and B stars, this includes lines from all spectra that have $S/N > 35$. For a few bright giant and supergiant O-stars with signal-to-noise ratios smaller than this value, line measurements are presented for the relatively strong Brα profile, and in the case of HD 190429 (O4I) and QZ Sge (O7.5Ia) for the Brβ and HeⅡ (6−7) and (7−9) transitions. For one B star, HD 191243 (B5II), only three Pfund series lines could be measured. This is due to a poorer $S/N$ of sub-band 1a compared to sub-bands 1b and 1d.

In the Be and LBV subgroups, lines could be measured with sufficient accuracy in all but two stars, ε Cap (B2.5Vpe) and τ Aqr (B1Ve). The $S/N$ of those two observations is quite low, 30 and 20, respectively, and the lines are not sufficiently prominent to be detectable in our ISO/SWS spectra.

4. Line trends and spectral classification of O and B stars

In discussing the trends in line strengths of O and B stars we separately consider luminosity classes Ia-II and III-V, because the behaviour of the hydrogen lines in the two groups is different. The difference is almost certainly connected to the density of the stellar wind. In main-sequence stars, which have weak winds, the line strength is dominated by temperature effects. As in optical spectra, one expects a gradual weakening of the lines towards higher
effective temperatures. In supergiant stars, which have dense winds, the strength of the lines connecting lower levels of a series (such as Br$\alpha$) are expected to be highly sensitive to the stellar mass-loss rate $\dot{M}$, or better stated, to the stellar mass flux $\dot{M}/4\pi R^2$. Indeed, in our data set Br$\alpha$ reverts from a strong absorption profile in B giants and dwarfs to a strong emission profile in B supergiants, suggesting that the line is sensitive to mass loss. The equivalent widths of the hydrogen lines are presented in Fig. 8 for the Brackett lines and in Fig. 9 for the Pfund lines. In these figures, the luminosity classes Ia-II are denoted by a square (and plotted slightly to the right of their spectral type); class III by a circle, and classes IV-V by a cross (and plotted slightly to the left of their spectral type). In order to quantify the behaviour of hydrogen lines with spectral type, we assign values to spectral types. Spectral types B0 to B9 are assigned the values 10 to 19. For the B-type dwarfs to giants, a quantitative trend is then derived by fitting the EW versus spectral type with a first-order polynomial of the form $A \times S.T. + B$, where S.T. ranges between 10 and 19 as defined above. This is done for 6 dominant hydrogen lines: Br$\alpha$, Br$\beta$, Pf$\gamma$, Pf$\delta$, Pf(11–5) and Pf(13–5), the results are presented in Table 6. We did not measure Pf(10–5), nor Pf(12–5) as we decided to focus on the behaviour among a wide range of upper levels. Hydrogen lines from higher transitions are too weak to be measured in a significant fraction of our sample. We do not extend the same strategy to O-type stars. Indeed, the extrapolation of the linear trend we apply for B-type stars does not provide a satisfactory fit to the data points for O-type stars. The O-type sample is too small to build a quantitative scheme of spectral classification. Moreover,
at least one O stars of our sample cannot be part of a general analysis of characteristics of normal early-type stars. Indeed, the O7 V star HD 47839 is a spectroscopic binary. The early B companion affects the spectrum significantly, making the hydrogen lines broader and stronger (Gies et al. 1997). Therefore O-type stars are discussed in a more qualitative way in Sect. 4.3.

4.1. B supergiants and bright giants

$\text{Br}\beta$ is mostly in emission while $\text{Br}\beta$ is the strongest in absorption of all the hydrogen lines observed, the others getting weaker with higher series and members. The hydrogen lines of B supergiants do not show a significant spectral-type dependence but remain roughly constant, although with a large scatter (see Figs. 8 and 9). This may be related to the variable nature of relatively strong lines in B supergiants. Outward propagating density enhancements (spectroscopically identified as discrete absorption components) and/or modulation of the overall mass-loss rate has been suggested as causes for the time variability of line strength and line shape (see Kaper 1998 for a review). For instance, Kaufer et al. (1996) suggest, on the basis of time-series analysis of $\text{H}o$ in B- and A-type supergiants, that observed variations are due to rotational modulation possibly induced by weak magnetic surface structures, stellar pulsations, and/or instabilities of the ionisation structure of the wind. In dwarf stars, the profiles are predominantly formed in the photosphere where these phenomena are expected to have only a minor impact on the line strength. Therefore, in dwarfs a dependence of line strength on spectral type may be expected (see Sect. 4.2).

Neutral helium lines are detected in O9.5-B3 stars, and can therefore be used to constrain the spectral type to earlier than B3. In the two O supergiants in our sample, the $S/N$ is unfortunately too poor to detect $\text{He}\lambda$. We did not attempt to use the line strength to set the sub-type within O9.5-B3 to avoid over-interpretation. We note that the $\text{He}\lambda$ is found to be systematically stronger in supergiants than in dwarfs stars (cf. Fig. 10).

4.2. B dwarfs and giants

In the B-type dwarfs and giants, all hydrogen lines are seen in absorption, their strengths increasing with later spectral type. This is most pronounced for the lowest Pfund series line observed ($\text{Pf}\gamma$), and is less so for higher Pfund series lines and Brackett series lines (Table 6). This behaviour suggests that these lines might provide a spectral-type, i.e. temperature diagnostic. All hydrogen lines show a similar first-order dependence, however, the slope for the Brackett lines is smaller than for the Pfund lines.

The most accurate diagnostic for determining the spectral type from the equivalent widths of these lines is to add a number of equivalent widths. Adding all the lines we measured gives the stronger slope, but not the best relation to recover spectral types. Indeed adding the $\text{EW}$ of the Pfund lines only, gives the same measure of goodness of fit with smaller errors on the measurements. It is therefore a preferred diagnostic.

We add the $\text{EW}$ of the four Pfund lines we measured. The best linear fit relation between spectral type and the summed $\text{EW}$ is given in Table 6. Using this relation, we are able to recover the spectral types of all twelve B dwarfs to giants used to define the fit, within two spectral sub-types. Among those, for 8 of the 12 stars we find the spectral type to within one sub-type, and for 6 of the 12 we recover the exact spectral type. This result is quite satisfactory, considering that we adopted a simple linear fit to describe the $\text{EW}$ versus spectral-type relation.

The presence of $\text{He}\lambda$ allows some refinement of our spectral-type estimates, as these lines appear only between spectral type O9 and B2 in dwarfs to giants. This allows us to assign $\alpha$ Pav, which was assigned type B4 considering only the hydrogen lines, its correct spectral type: B2.

Using the summed $\text{EW}$ of $\text{Br}\beta$ and $\text{Pf}\gamma$ allows for a linear relation to determine the spectral type, identical to the method described previously. The parameters of this relation are also given in Table 6. The linear fit recovers the spectral type of the 14 B-dwarfs and giants to within five spectral sub-types. Of the 14, for 11 the classification is accurate to within four sub-types; for 10 it is within two sub-types; for 6 it is within one subtype, and for three it is exact. At the extrema of the B classification, B0 and B9, the classification fails by five spectral sub-types, indicating earlier and later spectral types respectively. This suggests
one must use a higher order fit and/or one has to separate the spectral-type dependence of dwarfs, sub-giants and giants. Unfortunately, the data quality and sample size does not allow us to investigate this possibility. We note that the L'-band spectral range between 3.5 and 4.1 μm also contains some Humphreys series lines. However, these could not be used as their strength can only be accurately measured in late B-type stars.

Given the data quality and spectral coverage of our sample, it is not possible to distinguish between giants and dwarfs using the equivalent widths only. However, the full width at half maximum (FWHM) of the Brα line does allow giants and dwarfs to be separated. B-type dwarfs have a FWHM of more than 430 km s\(^{-1}\) (up to 665 km s\(^{-1}\)), after correction for the instrumental profile, and giants have a FWHM of between 330 and 430 km s\(^{-1}\). Supergiants that show a photospheric profile have even narrower Brα lines. The reason why a simple equivalent width measurement fails to achieve this distinction can be explained by the quality of our data. Indeed, the main source of error in measuring the EW is in the position of the continuum. Assuming Gaussian line shapes, and given our spectral resolution, the relative error in the EW is up to 2.5 times the relative error in the FWHM. We also tried to separate giants and dwarfs using the FWHM of Brβ and Pfγ, however, unfortunately without success.

### 4.3. O stars

Simple relations connecting line strength to spectral type, such as for B dwarfs and giants (see Sect. 4.2), cannot be derived for O-type stars. The reason is a too limited sample of stars that is only observed in the L'-band. The difference in behaviour between Pfγ and Brα also shows that mass loss plays an important role in the line formation process. Pfγ shows a modest dependence of EW on spectral class — dominated by temperature effects, while Brα shows a steep dependence — dominated by wind density effects. In the remainder of this section, we will concentrate on the latter line as a diagnostic for stellar mass loss \( \dot{M} \).

All O stars in the sample show emission in Brα, except for two late-type main-sequence stars, i.e. HD 47839 (O7 V) and HD 37468 (O9.5 V). The emission results from the presence of strong stellar winds in these stars (see e.g. Kudritzki & Puls 2000 for a review). This is illustrated in Fig. 11, where the measured Brα equivalent width is plotted versus mass-loss rate. For late O-type stars the Brα equivalent width includes a non-negligible contribution of He \( \lambda 4.049 \). The \( \dot{M} \) values have been determined using either the strength of the H\( \alpha \) profile as a diagnostic or using radio fluxes. Most values are from a compilation by Lamers & Leitherer (1993). Their \( \dot{M} \) rates are indicated by square symbols, while diamonds denote radio rates. Three additional measurements (from Puls et al. 1996; Kudritzki et al. 1999) are based on fitting of the H\( \alpha \) line. For three stars (\( \xi \) Ori, \( \epsilon \) Ori, and \( \alpha \) Cam) multiple mass-loss rate determinations are available. Intrinsic uncertainties in these determinations are typically 0.2–0.3 dex, which is also illustrated by the range in values found for the three stars. The rather large difference in derived mass-loss rate for \( \xi \) Ori (\( \dot{M}(\text{H}\alpha) = 10.2 \times 10^{-7} \) vs. \( \dot{M}(\text{radio}) = 3.2 \times 10^{-7} \) \( M_\odot \) yr\(^{-1} \)) is likely related to the greater uncertainty in the treatment of the H\( \alpha \) photospheric absorption as well as to the low flux densities at cm wavelengths, for low values of \( \dot{M} \). A clear relation between mass-loss rate and Brα equivalent width is present. Adopting an error of 0.2 (0.3) dex in the radio (H\( \alpha \)) rates and applying a weight average for the three stars for which multiple \( \dot{M} \) determinations are available, one finds a best fit linear relation:

\[
\log \dot{M} = (0.72 \pm 0.21) \log(-W_{\text{eq}, \text{Br}\alpha}) - (6.64 \pm 0.28).
\]

The most accurate prediction for the mass-loss rate from an equivalent-width measurement is expected if the observed \( W_{\text{eq}} \) is corrected for photospheric absorption and is plotted versus the equivalent width invariant \( Q \equiv M^2/(R^3/2T_\text{eff}^1/2 v_\infty) \), which is essentially related to the wind density (de Koter et al. 1998; Puls et al. 1996). This method requires accurate basic stellar parameters, which, as pointed out in this paper, are non-trivial to obtain if only infrared data is available. Also, the terminal velocity \( v_\infty \) of the stellar wind needs to be known. In O-type stars, this latter quantity is accurately determined from the blue-edge in P Cygni profiles of UV resonance lines.

### Table 6. Fits giving the relation between spectral type S.T. and EW (in Å) of Brackett and Pfund lines in B-type dwarfs to giants. For zero and first-order polynomials, we give the fit coefficients \( A \) (in Å/S.T.) and \( B \) (in Å) and their errors, as well as \( \sqrt{\chi^2/N} \) as a measure for the goodness of fit (which should be less than about unity). \( N \) is the number of stars for which data is available. “All” denotes the sum of all the individual lines given in the table, “Pfund” for the sum of Pfγ, Pfβ, Pf(11-5), and Pf(13-5), and “L'-band” refers to the sum of Brα and Pfγ. The most accurate spectral types may be derived from the “Pfund” lines.

<table>
<thead>
<tr>
<th>line</th>
<th>A</th>
<th>dA</th>
<th>B</th>
<th>dB</th>
<th>( \sqrt{\chi^2/N} )</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brα</td>
<td>0.41</td>
<td>0.05</td>
<td>1.98</td>
<td>0.79</td>
<td>0.41</td>
<td>15</td>
</tr>
<tr>
<td>Brβ</td>
<td>0.29</td>
<td>0.03</td>
<td>3.11</td>
<td>0.49</td>
<td>0.46</td>
<td>15</td>
</tr>
<tr>
<td>Pfγ</td>
<td>0.65</td>
<td>0.06</td>
<td>-2.23</td>
<td>0.91</td>
<td>0.53</td>
<td>14</td>
</tr>
<tr>
<td>Pfβ</td>
<td>0.65</td>
<td>0.05</td>
<td>-3.03</td>
<td>0.66</td>
<td>0.36</td>
<td>15</td>
</tr>
<tr>
<td>Pf(11-5)</td>
<td>0.57</td>
<td>0.04</td>
<td>-3.48</td>
<td>0.66</td>
<td>0.30</td>
<td>15</td>
</tr>
<tr>
<td>Pf(13-5)</td>
<td>0.61</td>
<td>0.05</td>
<td>-5.15</td>
<td>0.72</td>
<td>0.60</td>
<td>13</td>
</tr>
<tr>
<td>All</td>
<td>2.84</td>
<td>0.34</td>
<td>-2.00</td>
<td>5.34</td>
<td>0.23</td>
<td>12</td>
</tr>
<tr>
<td>Pfund</td>
<td>25.51</td>
<td>0.77</td>
<td>0.82</td>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>L'-band</td>
<td>15.34</td>
<td>0.38</td>
<td>0.79</td>
<td></td>
<td></td>
<td>14</td>
</tr>
</tbody>
</table>
In B stars with emission lines, most hydrogen lines are in emission in the 2.4–4.1 \( \mu \)m range. Those emission lines mainly originate from circumstellar material that are filling in (partially or completely) the atmospheric absorption lines. The nature of the circumstellar material surrounding the objects of this sample is very diverse. In Luminous Blue Variable stars, the emission lines originate from a dense wind. B[e] stars (see Lamers et al. 1999 for a review) have (sometimes strong) forbidden lines implying that there is a large volume of low-density gas near the star in which conditions are favourable for the excitation of these transitions.

It is now well established that “classical” Be stars are surrounded by dense, roughly keplerian circumstellar disks. The most convincing evidence for the presence of disks is derived from direct imaging at optical wavelengths (e.g. Quirrenbach et al. 1997) and at radio wavelengths (Dougherty et al. 1992). Besides imaging, other observed properties of Be stars are also naturally explained by the presence of a circumstellar disk. One of the defining characteristics of Be stars is the presence of (often double-peaked) H\( \alpha \) emission. The width of the H\( \alpha \) line scales with the projected rotational velocity of the photosphere (\( v \sin i \)) (e.g. Dachs et al. 1986). Both the double-peaked nature and the relation between width and \( v \sin i \) are consistent with the line emission being formed in a flattened, rotating disk surrounding the star (Poeckert et al. 1978).

In addition, the variations in the violet and red peaks of the H\( \alpha \) and other H\( i \) lines in the spectra of Be stars are explained due to spiral density waves in a non-self-gravitating keplerian disk (Telting et al. 1994). Such a keplerian disk geometry also explains the continuum linear polarisation caused by Thomson scattering of free electrons in the disk (e.g. Cote et al. 1987). The position angle of the polarisation is consistent with the orientation of the disk observed by imaging. Be star disks tend to have large densities, as derived from e.g. infrared excess (Waters et al. 1987). The disk radii probably vary from a fraction of a stellar radius (Coté et al. 1996) to many tens of \( R_\star \) (Waters et al. 1991).

We find no obvious correlation between spectral type and strength of the emission lines in the Be stars with luminosity class III to V (sometimes referred to as classical Be stars) in our sample (Figs. 5 and 6). Other studies report a similar lack of correlation between spectral type and amount of circumstellar gas, except perhaps when it comes to the maximum amount of emission at a given spectral type (see e.g. Dougherty et al. 1992 or Waters et al. 1986). We do not see double peaked lines at our resolution (\( \Delta \lambda / \lambda \approx 1200 \)). We also do not find evidence for forbidden line emission in the “classical” Be stars, in agreement with such a lack in optical spectra. Further investigation is needed to conclude about the presence of such lines in the spectra of the few B[e] of our sample.

He\( t \) emission lines are present in most stars with spectral type earlier than B3. We find a few O\( t \) emission lines, the stronger ones being at \( \lambda 2.8935 \) and \( \lambda 3.6617 \) in several classical Be stars of spectral type earlier than B3 as well as in Luminous Blue Variable stars and in the B[e] star HD 200775. We also find Fe\( ii \) and Mg\( ii \) emission lines in all three LBVs. The Fe\( ii \) lines are also present in the spectra of HD 105435 and HD 45677.

The sample of B stars with emission lines will be investigated in more detail in a forthcoming publication (Lenorzer et al. in prep.).
a number of simple empirical methods aimed at using the infrared spectrum to i) determine the spectral type and/or luminosity class, and ii) determine the mass-loss rate. The main results are:

1. In normal B-type giant to dwarf stars the Pfund lines, and to a lesser extent the Brackett lines, may be used to estimate the spectral type. We provide a simple formula to do this. The leading line of each series shows the most pronounced dependence. Helium lines help to improve this spectral classification, He\textsc{i} being present in late O-type and early B-type stars. All B-type giants and dwarfs have Bro in absorption. The full width at half maximum of this line may be used to discriminate between luminosity classes III and V, the line being broader for dwarfs.

2. In B-type supergiants the equivalent width of all measured hydrogen lines remains constant with spectral sub-type, although with a significant scatter. Bro is seen mostly in emission, while all other lines are in absorption. He\textsc{i} A3.0736 is systematically stronger in absorption compared to B-type supergiants and giants.

3. In normal O-type stars and in B-type supergiants, the Bro line is mostly in emission and provides a sensitive indicator of the mass-loss rate. We give a relation that uses the equivalent width of this line to estimate $M$.

4. Concerning hydrogen lines, the ones positioned in the L'-band seem best suited to derive physical properties of OB stars when compared to the diagnostics available in other atmospheric bands such as $K$-, $H$-, and $J$-band. The main reason is that the L'-band contains three different hydrogen series lines and includes the leading Brackett-series line. Concerning other species, the K-band seems to contain the most useful lines. This last remark, however, only applies to O-type stars (where e.g. C IV, N III and an unblended He II line are seen) and not to B-type stars which do not show lines of metal species in that wavelength range.

5. In our sample of Be, B[e], and Luminous Blue Variable stars we find no obvious correlation between spectral type and strength of the emission lines. Stars with spectral type earlier than B3 show He\textsc{i} lines, similar to normal B-type stars. Several emission line stars show O\textsc{i}, however not at spectral types later than B2.

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Appendix: Equivalent width measurements

The appendix is only available in electronic form at the CDS.

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