Observations of \( \text{H} \alpha \), iron, and oxygen lines in B, Be, and shell stars

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Abstract. We have carried out a spectroscopic survey of several B, Be, and shell stars in optical and near-infrared regions. Line profiles of the \( \text{H} \alpha \) line and of selected Fe\(^{\text{II}} \) and O\(^{\text{I}} \) lines are presented.

Key words. Stars: Be – line: profiles

1. Introduction

Observations of B, Be, and shell stars in different spectral regions are important for putting constraints on modeling these stars. Echelle spectrographs as well as the high sensitivity of modern detectors in the red part of the spectrum provide a wealth of the information contained in the whole visible and near infrared regions obtained simultaneously. The aim of this paper is a spectroscopic survey of line profiles of \( \text{H} \alpha \) and selected non-hydrogenic lines of iron and oxygen in the visual and near infrared region for selected bright B and Be stars. We mainly use the echelle observations secured using the HEROS (Heidelberg Extended Range Optical Spectrograph) spectrograph attached to the Ondřejov 2m telescope supplemented by several CCD coudé spectra.

2. Observations and data reduction

The present data are based on new spectroscopic observations of 13 B stars, 28 Be stars, and 8 shell stars. Our sample of stars contains objects of spectral types B0 – B9.5 and luminosity classes III, IV and V. Table I summarises the basic information about the observed objects, their HD and HR no’s, their name (if available), MK spectral type, luminosity class, and Julian dates of the observations. Some of these stars have never been observed before (to the best of our knowledge) in the near-infrared region. The spectra of these stars were obtained between January 2001 and November 2003 using the fiber-fed echelle spectrograph HEROS (for a brief description see Štefl & Rivinius 2000, Škoda & Šlechta 2002) attached to the Cassegrain focus of the 2m telescope at Ondřejov Observatory. All the basic data reduction processing, including bias subtraction, flat fielding, and wavelength calibration, have been done using the HEROS pipeline written by O. Stahl and A. Kaufer as an extension of basic MIDAS echelle context (see Stahl et al. 1995, also Škoda & Šlechta 2002b). Additional observations of several stars were secured using a CCD detector of a coudé spectrograph of the same telescope (Šlechta & Škoda 2002) and the data were reduced by the IRAF package.

3. Observed lines

3.1. The hydrogen \( \text{H} \alpha \) line

The \( \text{H} \alpha \) line in the stars of our sample was found to be either in absorption or in emission, however, an intermediate case between emission and absorption was also found. Our set of stars exhibits basically five different shapes of \( \text{H} \alpha \) line. We introduce corresponding stellar subclasses for our sample, namely

i. Emission is present, but it is completely below the continuum level. We will denote this subclass as \( \text{AbEm} \) (absorption with emission).

ii. The absorption part is below the level of continuum while the emission peak is above the continuum. The ratio of these two parts often varies at different phases for the same star. We will denote this subclass as \( \text{EmAb} \) (emission with absorption).

iii. The whole emission feature is completely above the continuum level. They will be denoted by \( \text{Em} \) (pure emission).

iv. We may also define the shell stars characterised by extremely sharp \( \text{H} \alpha \) absorption cores as one of the Be star phases. Since there is no intrinsic difference between Be and shell stars, we denoted them by Sh. Besides the shape of the \( \text{H} \alpha \) emission line profile, the presence of other sharp
Table 1. List of the B and Be stars in our sample. References to the spectral type are denoted by superscript numbers in parentheses, and the values of $T_{\text{eff}}$ are from Theodossiou & Danezis (1991).

| HD     | HR   | Name  | Sp. Type | $T_{\text{eff}}$ | JD–24 00 000 | JD–24 00 000 | Shape |
|--------|------|-------|----------|------------------|--------------|--------------|-------|
| 22780  | 1113 | 17 Tau| B6V(1)   | 12915 ± 303      | 53217.5656   | 53217.5434   | AbEm |
| 23302  | 1142 | 10 Cas| B9III(1) | 10700 ± 385      | 52931.3284   | 53204.5171   | EmAb |
| 36408B | 1847B| ι And | B6III(1) | 13810 ± 383      | 52619.9573   |              |       |
| 217675 | 8762 | 6984  | B6V(1)   | 12940 ± 1230     | 52721.8196   |              | AbEm |
| 171780 | 6984 | ι And | B7IV(1)  | 13810 ± 383      | 51779.0595   |              |       |
| 217675 | 8762 | 6984  | B6III(1) | 13810 ± 383      | 51779.0595   |              |       |
| 171406 | 6971 | V532 Ly| B5IV    | 15061 ± 374      | 52931.3284   | 53204.5171   | EmAb |
| 193911 | 7789 | B2Ve  | B0.5IV   | 30025 ± 2160     | 52682.7532   |              |       |
| 18552  | 894  | B1Ve  | B7IIV(2) | 12120 ± 623      | 51954.7961   |              |       |
| 23760  | 1165 | η Tau | B7IIIe(2)| 15310 ± 750      | 53216.5315   | 53216.4905   | EmAb |
| 29866  | 1500 | η Tau | B7IV(1)  | 12940 ± 1230     | 52648.8068   |              |       |
| 109387 | 4787 | κ Dra | B5III(2) | 15310 ± 750      | 52720.9752   |              |       |
| 175863 | 1929 | 25 Vul| B4Ve(3)  | 17100 ± 386      | 53182.4428   | 53182.4642   | Em    |
| 193911 | 7789 | 25 Vul| B6IIV(2) | 14340 ± 570      | 52525.9284   |              |       |
| 200120 | 8047 | 59 Cyg| B1Ve(2)  | 25340 ± 2164     | 51795.9049   |              |       |
| 203467 | 8171 | 6 Cep | B2.5Ve(2)| 18445 ± 1426    | 52721.0674   |              |       |
| 206773 | 2374 | B0Ve  | B7IV(1)  | 29230 ± 208      | 52484.0447   |              |       |
| 217891 | 8773 | β Psc | B5Ve(2)  | 15310 ± 750      | 53216.5717   | 53216.5525   | Em    |
| 23862  | 1180 | EE Cep| B5Ve(2)  | 12120 ± 623      | 52526.1050   |              |       |
| 37202  | 1910 | 28 Tau| B8IIV(1) | 12120 ± 623      | 51797.0884   |              |       |
| 30658  | 2568 | ψ Aur | B1IVe(2) | 25570 ± 3652     | 51897.9234   |              |       |
| 142926 | 5938 | 4 Her | B1Ve(2)  | 12300 ± 945      | 52721.9337   |              |       |
| 162732 | 6664 | 88 Her| B7IV(1)  | 12915 ± 393      | 53217.4040   | 53217.4229   | EmAb |
| 171406 | 6971 | V532 Ly| B5Ve(3)| 17100 ± 386      | 53182.3954   | 53182.4168   | EmAb |
| 179343 | 02°3815| BD+40°2915| B9V(1)| 10580 ± 373      | 53216.4505   | 53216.4034   | EmAb |
| 217050 | 8731 | EW Lac| B3IVe(2) | 18445 ± 1426    | 53217.3848   | 53217.3731   | Sh    |
| 358    | 15   | α And | B9Iv(1)  | 10700 ± 385      | 51779.1187   |              |       |
| 886    | 39   | γ Peg | B2IV(3)  | 22400 ± 1393     | 51771.0511   |              |       |
| 23873  | 23°561| BD+23°561| B9V(1)| 10340 ± 465      | 52651.0012   |              |       |
| 24760  | 1200 | ε Per | B0.5V(5)| 30000            | 52648.7495   |              |       |
| 34759  | 1749 | ρ Aur | B3V(7)   | 15310 ± 750      | 52351.9306   |              |       |
| 36408  | 1847A| ζ Dra | B7III(8)| 12940 ± 1230     | 52720.8740   |              |       |
| 44743  | 2294 | β CMa | B6III(1)| 26105 ± 1779     | 52720.7954   |              |       |
| 87901  | 3982 | α Leo | B7IV(6)  | 12120 ± 623      | 51925.0219   |              |       |
| 120315 | 5191 | η UMa | B3V(7)   | 18445 ± 1426     | 52618.2262   |              |       |
| 138749 | 5778 | θ CrB | B6IIV(1) | 14340 ± 570      | 52693.1422   |              |       |
| 155763 | 6396 | η Her | B3IV(8)  | 13810 ± 383      | 52002.4133   |              |       |
| 160762 | 6588 | θ Her | B3IV(9)  | 18445 ± 1426     | 51787.9064   |              |       |
| 164852 | 6738 | 96 Her| B3IV(10)| 18445 ± 1426     | 52722.1490   |              |       |

References: (1) – Jaschek et al. (1989); (2) – Sliepcevich (1989c); (3) – SIMBAD; (4) – Levy & Levato (1975); (5) – Morgan et al. (1955); (6) – Murphy et al. (1986).
photospheric absorption lines which will be referred to as “shell lines” were also used for defining this subgroup. v. The last subclass consists of normal B stars with Hα absorption lines. They are included in our analysis as a kind of standard star. We denote them by Ab.

Our five subclasses represent a qualitative estimate of the Hα line profile in our present observations. Table I lists the stars according to these subclasses.

### 3.2. Non-hydrogen emission lines

There is a number of non-hydrogen emission lines in the spectra of Be stars. The most striking emission features are produced by iron, helium, and oxygen. In addition to the hydrogen lines, these non-hydrogenic lines carry supplementary information coming from different regions of the stellar envelope depending on their depth of formation.

#### 3.2.1. Iron lines

Iron lines bring a lot of information from the circumstellar envelope depending on their depth of formation. They are often present in the spectra of Be stars. An interesting fact about Fe II lines is that they appear in the emission spectrum, however, in the approximate theoretical spectrum, which was calculated under the simplified assumption of a LTE static plane-parallel atmosphere, they are completely missing. This indicates that the excitation mechanism is connected more probably with the atomic structure of Fe II and the corresponding NLTE pumping than with some global density changes or even iron overabundance. However, such a conclusion is to be verified by detailed NLTE calculations. We selected several strong lines mostly from the quartet system for our measurements.

Although the list of available Fe II lines is quite long, only several of them are useful for further analysis, in particular the 4233 Å line from the multiplet (27), the 4584 Å line from the multiplet (38), 6148 and 6456 Å lines from the multiplet (74), and 7516 and 7712 Å lines from the multiplet (73). Note that the 6148 Å line itself is a blend of two neighbouring Fe II lines. Due to its vicinity to the Hα line the Fe II 6456 Å line was present in the Hα spectrograms that were obtained with the CCD coudé camera.

The near-infrared line Fe II 7712 Å was severely contaminated by telluric lines in the band 7600 – 7700 Å. However, this line was sometimes strong enough to be measurable in 13 stars of our sample. In ten of them the line was in emission. Other Fe II lines, namely the 7516, 6456, and 6458 Å lines are also in emission. However, another Fe II line, which is not listed in the multiplet tables of Moore (1972), appeared to be quite strong in the synthetic spectra and may be possibly misidentified with the Fe II 7516 Å line. This line has a wavelength of 7513.162 Å and arises from the transition 5s e6D0/2 → 5p w6Pp 7/2. For simplicity we will identify this feature with the wavelength 7516 Å in the figures. In most cases the iron line Fe II 6516 Å was not detectable due to the huge number of telluric lines.

| Star       | 4233 | 4584 | 5168 | 5235 | 5317 | 5368 | 6432 | 6456 | 7462 | 7516 | 7712 |
|------------|------|------|------|------|------|------|------|------|------|------|------|
| HR 1847B   | +    | +    | +    |      |      |      |      |      |      |      |      |
| φ And      |      |      |      |      |      |      |      |      |      |      |      |
| β CMi      |      |      |      |      |      |      |      |      |      |      |      |
| V974 Her   |      |      |      |      |      |      |      |      |      |      |      |
| o Cas      | +    | +    | +    | +    |      |      |      |      |      |      |      |
| γ Cas      |      |      |      |      | +    |      |      |      |      |      |      |
| φ Per      | +    | +    | +    |      |      |      |      |      |      |      |      |
| HR 894     |      |      |      | +    |      |      |      |      |      |      |      |
| ψ Per      |      |      |      |      |      | +    |      |      |      |      |      |
| HR 1500    | +    | +    | +    | +    |      |      |      |      |      |      |      |
| κ Dra      |      |      |      |      |      |      | +    |      |      |      |      |
| HD 175863  |      |      |      |      |      |      |      | +    |      |      |      |
| 25 Vul     |      |      |      |      |      |      |      |      |      |      |      |
| 59 Cyg     |      |      |      |      |      |      |      |      |      |      |      |
| 6 Cep      |      |      |      |      |      |      |      |      |      |      |      |
| HD 206773  |      |      |      |      |      |      |      |      | +    |      |      |
| β Psc      |      |      |      |      |      |      |      |      |      |      |      |
| EE Cep     |      |      |      |      |      |      |      |      |      |      |      |
| 28 Tau     |      |      |      |      |      |      |      |      |      | +    |      |
| ζ Tau      |      |      |      |      |      |      |      |      |      |      | +    |
| 4 Her      |      |      |      |      |      |      |      |      |      |      | +    |
| 88 Her     |      |      |      |      |      |      |      |      |      |      |      |
| HD 179343  |      |      |      |      |      |      |      |      |      |      |      |
| EW Lac     |      |      |      |      |      |      |      |      |      |      |      |
| HD 23873   |      |      |      |      |      |      |      |      |      |      |      |
| ρ Aur      |      |      |      |      |      |      |      |      |      |      |      |
| β CMA      |      |      |      |      |      |      |      |      |      |      |      |
| α Leo      |      |      |      |      |      |      |      |      |      |      |      |
| η Uma      |      |      |      |      |      |      |      |      |      |      |      |
| θ CrB      |      |      |      |      |      |      |      |      |      |      |      |
| ζ Dra      |      |      |      |      |      |      |      |      |      |      |      |
| ε Her      |      |      |      |      |      |      |      |      |      |      |      |

### 3.2.2. The oxygen infrared triplet O I 7772–5 Å

The most dominant oxygen line in the visible and near infrared spectra of Be stars is the near IR triplet line at 7772, 7774, 7775 Å emerging from the transition 3s 5S0 → 3p 5P. Other transitions between quintet levels which fall into the visual region are missing in the spectra.

### 4. Description of the online material

Results of our observations are plotted in the online Appendix. It contains an atlas of the individual line profiles sorted and ordered according to the Table I. For each star, the Hα and O I 7772–5 Å lines are plotted. Iron lines are plotted for each observation where they were available. The list of Fe II lines presented is listed in the Table II.

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Online Material
Appendix A: Atlas of individual line profiles

Note that the panels which contain more than one profile the spectra are arbitrarily shifted by 0.2, 0.4 and 0.6 below or above the continuum level.

A.1. AbEm subclass

Fig. A.1. Profiles of Hα and OI 7772−5 Å lines of HR 1113.

Fig. A.2. Profiles of Hα and OI 7772−5 Å lines of 17 Tau.
Fig. A.3. Profiles of Hα, Fe II 5169, 5235, 5317 Å, and O I 7772–5 Å lines of HR 1847B.

Fig. A.4. Profiles of Hα, Fe II 5169, 5235, 5317 Å, and O I 7772–5 Å lines of ω And.
A.2. EmAb subclass

Fig. A.5. Profiles of Hα, Fe II 6456 Å, and O I 7772−5 Å lines of 10 Cas.

Fig. A.6. Profiles of Hα, Fe II 4233, 4584 Å, and O I 7772−5 Å lines of φ And.

Fig. A.7. Profiles of Hα and O I 7772−5 Å lines of OT Gem.
Fig. A.8. Profiles of Hα, Fe II 5169, 5235, 6456, 7712, and O I 7772–5 Å lines of β CMi.

Fig. A.9. Profiles of Hα, Fe II 77712 Å, and O I 7772–5 Å lines of V974 Her (HD 164447).

Fig. A.10. Profiles of Hα and O I 7772—5 Å lines of HR 6984 (HD 171780).
Fig. A.11. Profiles of Hα and OI 7772−5 Å lines of 60 Cyg.

Fig. A.12. Profiles of Hα and OI 7772−5 Å lines of β Cep.

Fig. A.13. Profiles of Hα and OI 7772−5 Å lines of V360 Lac.
A.3. Em subclass

Fig. A.14. Profiles of Hα, Fe II 4233, 4584, 5169, 5235, 5317, 7516, 7712 Å, and O I 7772−77 Å lines of o Cas.

Fig. A.15. Profiles of Hα, Fe II 4233, 4584, 5169, 5235, 5317, 7516, 7712 Å, and O I 7772−77 Å lines of γ Cas.

Fig. A.16. Profiles of Hα, Fe II 4233, 4584, 5169, 5235, 5317, 7516, 7712 Å, and O I 7772−77 Å lines of φ Per.
Fig. A.17. Profiles of Hα, Fe II 5169, 5235, 5317 Å, and OI 7772–5 Å lines of HR 894.

Fig. A.18. Profiles of Hα and Fe II 6432, 6456, 7712 Å lines of ψ Per.

Fig. A.19. Profiles of Hα and OI 7772–5 Å lines of η Tau.
Fig. A.20. Profiles of Hα, Fe II 5169, 5235, 5317 Å, and O I 7772–5 Å lines of HR 1500.

Fig. A.21. Profiles of Hα, Fe II 4233, 4584, 5169, 5235, 5317, 5363, 6456, 7516, 7712 Å, and O I 7772–5 Å lines of κ Dra.

Fig. A.22. Profiles of Hα, Fe II 6456, 7712 Å, and O I 7772–5 Å lines of HD 175863.
Fig. A.23. Profiles of Hα, Fe II 5169, 5235, 5317 Å, and O I 7772−5 Å lines of 25 Vul.

Fig. A.24. Profiles of Hα, Fe II 7516, 7712 Å, and O I 7772−5 Å lines of 59 Cyg.

Fig. A.25. Profiles of Hα, Fe II 4233, 4584, 5169, 5235, 5317, 6456, 7516, 7712 Å, and O I 7772−5 Å lines of 6 Cep.
Fig. A.26. Profiles of H\(\alpha\), Fe\(\text{II}\) 7516, 7712 Å, and O\(\text{I}\) 7772–5 Å lines of HD 206773.

Fig. A.27. Profiles of H\(\alpha\), Fe\(\text{II}\) 7516, 7712 Å, and O\(\text{I}\) 7772–5 Å lines of β Psc.

Fig. A.28. Profiles of H\(\alpha\), Fe\(\text{II}\) 7516, 7712 Å, and O\(\text{I}\) 7772–5 Å lines of EE Cep.
A.4. Sh subclass

Fig. A.29. Profiles of H\textsc{$\alpha$}, Fe\textsc{II} 4233, 4584, 5169, 5235, 5317, 7516, 7712 Å, and O\textsc{I} 7772–5 Å lines of 28 Tau.

Fig. A.30. Profiles of H\textsc{$\alpha$}, Fe\textsc{II} 4233, 4584, 5169, 5235, 5317, 7516, 7712 Å, and O\textsc{I} 7772–5 Å lines of ζ Tau.

Fig. A.31. Profiles of H\textsc{$\alpha$} and O\textsc{I} 7772–5 Å lines of ψ\textsuperscript{9} Aur.
Fig. A.32. Profiles of $H_{\alpha}$, Fe II 4233, 4584, 5169, 5235, 5317, 7712 Å, and O I 7772−5 Å lines of 4 Her.

Fig. A.33. Profiles of $H_{\alpha}$, Fe II 6456, 7712 Å, and O I 7772−5 Å lines of 88 Her.

Fig. A.34. Profiles of $H_{\alpha}$, Fe II 6516 Å, and O I 7772−5 Å lines of HR 6971 (HD 171406, V 532 Lyr).
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**Fig. A.35.** Profiles of Hα, Fe II 7712 Å, and OI 7772–5 Å lines of HD 179343.

**Fig. A.36.** Profiles of Hα, Fe II 6456, 7516, 7712 Å, and OI 7772–5 Å lines of EW Lac.
A.5. Ab subclass

Fig. A.37. Profiles of Hα and OI 7772–5 Å lines of α And.

Fig. A.38. Profiles of Hα and OI 7772–5 Å lines of γ Peg.

Fig. A.39. Profiles of Hα, FeII 7712 Å, and OI 7772–5 Å lines of HD 23873.
Fig. A.40. Profiles of Hα, Fe II 6516 Å, and O I 7772–5 Å lines of ε Per.

Fig. A.41. Profiles of Hα, Fe II 5169, 6456, 7516, and O I 7772–5 Å lines of ρ Aur.

Fig. A.42. Profiles of Hα and O I 7772–5 Å lines of HR 1847A.
Fig. A.43. Profiles of $\text{H}\alpha$, Fe $\text{II}$ 7462 Å, and O $\text{I}$ 7772–5 Å lines of $\beta$ CMa.

Fig. A.44. Profiles of $\text{H}\alpha$, Fe $\text{II}$ 5169 Å, and O $\text{I}$ 7772–5 Å lines of $\alpha$ Leo.

Fig. A.45. Profiles of $\text{H}\alpha$, Fe $\text{II}$ 5169 Å, and O $\text{I}$ 7772–5 Å lines of $\eta$ UMa.
Fig. A.46. Profiles of Hα, Fe II 5169 Å, and O I 7772–5 Å lines of θ CrB.

Fig. A.47. Profiles of Hα, Fe II 4233, 4584, 5169, 5235, 5317, 6456 Å and O I 7772–5 Å lines of ζ Dra.

Fig. A.48. Profiles of Hα, Fe II 5169, 5235, 5317 Å, and O I 7772–5 Å lines of ι Her.
Fig. A.49. Profiles of Hα and O I 7772 – 5 Å lines of 96 Her.