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Zaal, P.A.; Waters, L.B.F.M.; Marlborough, J.M.; Geballe, T.R.

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Emission features in Brα and Brγ spectra of normal O and B stars*

P.A. Zaal[1], L.B.F.M. Waters[1,2], T.R. Geballe[3], and J.M. Marlborough[4]

[1] Astronomical Institute Anton Pannekoek, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
[2] SRON Laboratory for Space Research Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands
[3] Joint Astronomy Center, 660 N A'ohoku Place, Hilo, Hawaii 96720, USA
[4] Department of Physics and Astronomy, University of Western Ontario, London, Ontario, N6A 3K7, Canada

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Abstract. We present high resolution Brα and Brγ spectra for 15 near main-sequence O and B stars in a broad range in $v \sin i$ and with spectral type between O9–B2. The HI infrared lines probe the outer regions in the atmosphere and the onset of the stellar wind. The slowly rotating stars (with $v \sin i < 50\,\mathrm{km\,s^{-1}}$) show weak, single-peaked emission features on top of a broad absorption line. The most likely explanation is a non-LTE effect in the outer photosphere causing emission at line center. The slow rotators include two β Cephei stars, both of which also show HeI (4.049 μm) emission. This indicates a significant increase in the degree of ionization in the outer layers of these B2-3 stars. For the higher $v \sin i$ stars we find two cases (out of six) in which weak, double-peaked emission is visible on top of the photospheric absorption. These two stars probably have low-density discs which are apparent only in the infrared HI lines (Zaal et al., 1995).

Key words: stars: atmospheres – stars: early-type – stars: circumstellar matter – infrared: stars – line: formation

1. Introduction

The structure of the extended stellar atmospheres of O and B dwarfs is not well understood. In the spectral type range O9–B3 radiative forces become rapidly less important as the luminosity of the star drops to later spectral types, allowing other effects such as pulsation, rotation and magnetic fields to play a more prominent role. These cause a wide variety in spectral subclasses depending on which force, or combination of forces, dominates and also at which wavelength the star is observed.

From the UV we know these stars have a radiatively driven wind with mass loss rate varying from 10^{-7} $\mathrm{M_\odot yr^{-1}}$ at O9 to 10^{-10} $\mathrm{M_\odot yr^{-1}}$ at B3. The P-Cygni profiles found in the UV lines of O stars and the blue-shifted absorption wings found in the UV lines of early-B stars, reveal the presence of high-velocity winds (about 500–3000 $\mathrm{km\,s^{-1}}$), which are assumed to be roughly spherical (but not homogeneous).

However, optical and infrared observations show that in some cases the envelope is not spherically symmetric; examples are the B[e] and Be stars. Interferometric observations at optical and radio wavelengths demonstrate directly that the envelopes of Be stars are indeed flattened (Mourard et al., 1989; Dougherty & Taylor, 1992; Stee et al., 1994). Also the optical continuum shows linear polarization caused by electron scattering. The Hα line shows a double-peaked emission profile whose width is correlated with $v \sin i$, and at longer wavelengths there is an excess of radiation due to free-free and free-bound continuum emission from the ionized circumstellar gas.

The discovery of strong Brα (4.05 μm) emission in two slowly rotating "normal" OB stars, τ Sco, B0.2V (Waters et al., 1993) and 10 Lac, O9V (Murdoch et al., 1994), with $v \sin i$ of 22 and 31 $\mathrm{km\,s^{-1}}$, respectively, has led to the suggestion that slowly rotating stars are capable of producing low-density discs (Waters et al., 1993). A theoretical study of the IR spectrum of OB stars with low-density discs (Zaal et al., 1995) has shown that the HI lines in the infrared are sensitive indicators for the presence of such a disc. The densities predicted in the *Wind Compressed Disc* (WCD) model of Bjorkman & Cassinelli (1993) would perhaps lead to detectable emission in the IR lines while leaving the Hα line unaffected (Zaal et al., 1995). However, the rotation velocities needed for disc formation are above 50–60% of the critical rotation speed ($\mathrm{V}_{rot} > 230-300$ $\mathrm{km\,s^{-1}}$). This would imply that both τ Sco and 10 Lac are seen pole-on.

A different explanation for the emission lines, seen in the infrared for 10 Lac and τ Sco, is that HI IR line emission arises as a result of non-LTE effects in the atmospheres of O and early-B stars (Murdoch et al., 1994). The emission is due to a combination of stimulated emission ($h\nu/kT << 1$) in the infrared and departures from LTE in the line forming regions for the upper and lower quantum levels involved ($b_{up} > b_{lo}$). The main constraint for this mechanism to operate for the HI

Send offprint requests to: P.A. Zaal

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IR lines is that hydrogen needs to be mainly ionized (see Sect. 3.1).

Both effects always need to be considered, while the possible presence of a low-density disc depends on the rotation velocity of the star. Non-LTE model calculations (Hubeny & Lanz, 1995; Chang et al., 1991; Carlsson et al., 1992) have improved much over the last two decades and now provide good insight into the HI IR line formation in the atmospheres of hot stars. Sigut & Lester (1995) describe the line formation for MgII Rydberg transitions in B stars. For spectral types earlier than B3, where HI will be mainly ionized, the HI IR lines will go into emission in the same way as MgII in case of the B stars. These HI lines will be highly sensitive to departures from LTE in the outer atmosphere. This effect, together with the possibility of disc formation, makes the HI IR lines difficult to interpret, but at the same time also very interesting and powerful as a tool to study the structure of these hot atmospheres.

Based on these considerations we decided to investigate observationally the IR spectra of "normal" OB stars with spectral type varying from O9 to B3. The sample of 15 stars which was studied is given in Table 1. For these stars $v \sin i$ ranges from 10 to about 330 $\mathrm{km\,s^{-1}}$. Nine of the 15 stars observed showed emission features in the Brα and/or Brγ line. The observed high-resolution line profiles are very diverse, showing evidence for non-LTE effects in the atmosphere and possibly also the existence of low-density discs around B stars. Furthermore two β Cephei stars show Brα emission and strong HeI 4.049 μm emission.

A description of the observations is given in Sect. 2. Each spectrum will be discussed in detail in Sect. 3. Finally the conclusions will be given in Sect. 4.

Table 1. The program and template stars. Given is the HD number, the name, spectral type, V magnitude and $v \sin i$ and which lines are observed. For all the O stars, τ Sco and 22 Sco the spectral type is derived from Walborn (1982) and for all the other stars the spectral type is derived from the Bright Star Catalogue and its supplement. The V magnitude and $v \sin i$ are derived from the BSC. For HD195965 the $v \sin i$ is estimated from the high-dispersion IUE spectra. ι Her and θ Oph are the β Cephei stars.

Star HD	Name	Spectral type	V	$v \sin i$ [$\mathrm{km\,s^{-1}}$]	Lines
214680	10 Lac	O9V	4.88	31	Brα,γ
209481	14 Cep	O9V:	5.56	130:	Brα,γ
193322	HR7767	O9V:((n))	5.84	110:	Brγ
155889		O9IV	6.55	40	Brα
149438	τ Sco	B0.2V	4.73	24	Brα,γ
195965		B0V	6.98	> 200	Brγ
218376	1 Cas	B0.5IV	4.85	50	Brα
180968	2 Vul	B0.5IV	5.43	332	Brα
203938		B0.5IV	7.08	220	Brα,γ
157056	θ Oph	B2IV	3.27	35	Brα
148605	22 Sco	B2.5V	4.79	232	Brα
138485	ζ^4 Lib	B2Vn	5.50	256	Brα,γ
142114	2 Sco	B2.5Vn	4.59	308	Brα,γ
120315	η UMa	B3V	1.86	205	Brα,γ
160762	ι Her	B3IV	3.80	11	Brα
141527	R CrB	G0Iep	5.85	18	Brα
219134	HR8832	K3V	5.56	–	Brα
201091	61 Cyg	K5V	5.21	< 17	Brγ
141637	1 Sco	B3V	4.64	300	Brγ

2. The observations

The observations reported here were obtained at United Kingdom Infrared Telescope (UKIRT) on July 4th and 5th, 1994, using the echelle of the facility grating spectrometer, CGS4. The spectral resolution was 14,000 at 4.05 μm (Brα) and 15,000 at 2.17 μm (Brγ), corresponding to velocity resolutions of 22 km $\mathrm{s^{-1}}$ and 20 $\mathrm{km\,s^{-1}}$, respectively. The spectral coverage is about 1450 $\mathrm{km\,s^{-1}}$ and 1300 $\mathrm{km\,s^{-1}}$ for Brα and Brγ, respectively. Integration times were varied according to the brightness of the star and the possibility that a weak emission feature was being detected. Weather conditions were good except in the beginning of the first night, which we used for the more easily observable Brγ line. Wavelength calibration was achieved by observation of the krypton and argon lamps, telluric absorption lines and NGC6572. The velocity scales are believed to be accurate to about 3 $\mathrm{km\,s^{-1}}$.

The atmospheric and instrumental transmission and interference fringes (caused by internal reflections within the instrument) were canceled by ratioing using stellar standards. For the Brα line we used HD219134 (HR8832) and HD141527 (R CrB) as template stars. The Brα spectrum of HD219134 was corrected artificially by removing an unidentified weak absorption feature at about –500 $\mathrm{km\,s^{-1}}$ from the central wavelength of Brα. Because of its peculiar spectrum R CrB is a good template star, since it has a strong dust continuum without HI absorption lines.

For the Brγ line we used HD201091 (61 Cyg) and the rapidly rotating star HD141637 (1 Sco, B3V) as template stars. We used 1 Sco instead of R CrB because the latter appeared to have a stronger fringe pattern, probably due to unstable weather during the beginning of this specific night. In order to use the spectrum of 1 Sco as a template star the broad photospheric absorption profile had to be removed. This was done by dividing the original spectrum of 1 Sco by a smoothed version of the original 1 Sco spectrum and multiplying it by the smoothed spectrum of R CrB. This resulted in a template spectrum for which the small-scale structure (sky and fringe) was taken from 1 Sco and the global pattern from R CrB, assuming it has a flat continuum. The same method to obtain an alternate template star was used in one other case. To reduce the Brα spectrum of τ Sco we used the Brα spectrum of HD142114 (2 Sco) as template instead of R CrB. R CrB was not suitable anymore because it was observed at the beginning of the set while τ Sco was observed at the end of the set (more than 2 hours time difference).

Quotient spectra are optimized by scaling the equivalent width (EW) of the telluric lines of the template spectrum to the stellar spectrum. In some of the spectra residual fringes are still visible. In these cases the spectrum of the star itself has a slightly different fringe pattern than the fringe pattern in the spectrum of the ratio star and therefore could not be completely removed. In the reduction we used a cross-correlation to correct

Table 2. Quantitative measurements for the observed spectra given in Fig. 1. The name, equivalent width (EW), FWHM, line-velocity of central peak or absorption, the line over continuum value of the central absorption or emission and the signal to noise ratio (S/N) of the spectrum are given. In the last column we note which template is used. Note that the EW given for the absorption component of Brγ spectra and for some Brα spectra as well is a lower limit (see section 2)

Name	Line	Feature	EW [Å]	FWHM [km s^{-1}]	Line vel. [km s^{-1}]	I_l/I_c	S/N	Template star [HD]
10 Lac	Brα	absorption	5.3	–	–	–	90	219134
	Brα	emission	−5.1	65	−9	1.64		
	Brγ	absorption	2.3	307	−12	0.93	150	201091
	Brγ	emission	−0.2	63	−26	1.05		
14 Cep	Brα	emission	−6.9	300	−30	1.20	30	219134
	Brγ	absorption	3.0	400	−180	0.95	140	219134
	Brγ	emission	−1.0	184	−122	1.04		
HD193322	Brγ	absorption	2.2	450	12	0.94	140	201091
HD155889	Brα	emission	−2.0	73	3.6	1.28	14	141527
τ Sco	Brα	emission	−10.1	85	−4	1.87	66	142114
	Brγ	absorption	4.3	500	2	0.89	210	141637
	Brγ	emission	−0.4	66	−8	1.08		
HD195965	Brγ	flat	–	–	–	–	36	201091
1 Cas	Brα	absorption	8.3	700	–	0.90	40	219134
	Brα	emission	−1.2	70	−22	1.12		
2 Vul	Brα	emission (V)	−0.3	29	−197	1.10	43	141527
	Brα	emission (R)	−0.4	30	232	1.10		
HD203938	Brα	absorption	4.7	400	–	0.93	55	141527
	Brα	emission (V)	−0.7	78	−128	1.07		
	Brα	emission (R)	−0.7	100	130	1.06		
	Brγ	absorption	1.3	230	10	0.91	125	219134
θ Oph	Brα	absorption	7.9	386	−1.4	0.88	71	141527
	Brα	emission	−0.62	53	2.7	1.08		
22 Sco	Brα	absorption	5.0	545	30	0.90	25	141527
ζ^4 Lib	Brα	absorption	–	–	–	–	16	141527
	Brγ	absorption	4.1	517	−1	0.89	100	141637
2 Sco	Brα	absorption	4.5	–	–	0.93	39	141527
	Brγ	absorption	5.4	680	8	0.83	150	141637
η UMa	Brα	absorption	5.5	370	3	0.90	180	141527
	Brγ	absorption	4.6	470	7	0.86	110	141637
ι Her	Brα	absorption	5.6	237	0.0	0.85	84	141527
	Brα	emission	−0.5	37	1.2	1.11		
	HeI	emission	−0.6	33	5.6	1.12		

for possible phase shift between the two fringes, before dividing by the spectrum of the ratio star. Note that the shifts determined from this cross-correlation are small compared to the spectral resolution. Normalization of the continuum was done by making a linear fit through two points at the wavelength extrema of the spectrum. For stars with a large $v \sin i$ the limited width of the detector in the dispersion direction makes it difficult to obtain a good determination of the continuum level. Model calculations of photospheric lines might lead to re-determination of the continuum level in several cases.

The spectra are shown in Sect. 3 and the corresponding line parameters and template stars are given in Table 2. For seven stars in this sample we have both Brα and Brγ spectra, for six stars Brα only, and for two stars Brγ only. All spectra are corrected for the motion of the earth, sun and radial velocity of the star (from the Bright Star Catalogue and its supplement).

The parameters given in Table 2 were obtained as follows. For lines for which an emission feature was superimposed on a broad absorption line, the emission was removed and the residual absorption profile fitted with a polynomial. The interpolated residual was then subtracted from the original spectrum, yielding a spectrum which contained only the emission component. Then the EW, the FWHM, the line velocity of the central emission (or absorption), and the line to continuum ratio were determined by using a gaussian fit. This was done only in case where the S/N (see Table 2) was sufficient. Note that this discrimination between emission and absorption is non-physical and was used only to obtain an unambiguous method of measuring the specific line strengths. When the line profile was asymmetric, the line velocities were determined by taking the velocity of the local maximum or minimum (instead of taking the peak velocity of the gaussian). The S/N ratio was determined from the root mean square (RMS) fluctuations at the extrema of the spectrum.

The equivalent width (EW) of the absorption component of Brα and Brγ spectra (as given in Table 2) is in most cases an lower limit because the full width zero intensity (FWZI) is in most cases larger than the spectral coverage. This is mainly due to Stark broadening or due to the large $v \sin i$ of the star.

3. Description of the observed spectra

Of all 13 program stars observed at Brα 9 have emission and at least 4 of the 9 show both Brα and Brγ emission. If the sample is divided into two groups, with $v \sin i > 180$ km s^{-1} and $v \sin i < 180$ km s^{-1}, 7 of the 8 slow rotators have line emission while only 2 of the 7 rapid rotators show line emission. 180 km s^{-1} is about the threshold $v \sin i$ for disc formation in the WCD model (Bjorkman & Cassinelli, 1993). About 10% of the O9/B2 stars are known to have Hα emission (Jaschek & Jaschek, 1983). Although our sample is small, this suggests that the Brα (or Brγ) line is more frequently observed in emission in slow rotators than is the Hα line. Indeed several stars in our sample show Brα emission but no Hα emission (τ Sco, 10 Lac and 1 Cas).

In order to give a more detailed description we subdivide our sample into four groups of stars: (1) late-O and early-B stars with $v \sin i < 180$ km s^{-1}, (2) rapidly rotating B stars, (3) β Cephei stars, and (4) others. The commonly accepted physical background of each of the subsets is discussed, followed by a detailed description of the observed spectra. The name, spectral type and $v \sin i$ (km s^{-1}) given, are from the Bright Star Catalogue (Hoffleit & Jaschek, 1982) and its supplement (Hoffleit et al., 1983).

3.1. The late-O and early-B stars with $v sini < 180$ kms^{-1}

The stars in this subset are τ Sco, 10 Lac, 1 Cas and HD193322 (see Table 1). None of the stars in this subset is known to have (or to have shown) Hα emission. 14 Cep (spectroscopic binary) and HD155889 are discussed in the last section (others) because their spectra show or have shown Hα emission.

Because of high temperatures in the atmospheres of these stars non-LTE effects are important, especially for line formation in the infrared. In such a case non-LTE effects give rise to a different atmospheric structure, i.e. different T(r) and ρ(r). Also the departure of the level populations of the quantum levels involved from their LTE values causes some lines to go into emission.

These lines go into emission because of the combination of stimulated emission ($h\nu/kT << 1$) in the infrared and departures from LTE for the upper and lower quantum levels involved ($b_{up} > b_{lo}$). The mechanism is thought to be the same as that leading to emission in the Rydberg transition of MgI at 12 μm in the solar spectrum (Murcray et al., 1981; Carlsson et al., 1992). The main constraint for this mechanism to operate is that the dominant ionization stage of the element is one higher than that of the transition being considered.

The Stark broadened wings in the HI IR lines are formed in the deeper photosphere where its departure coefficients are still equal to 1, while the line core is formed in the outer photosphere where depopulation takes place for quantum levels higher than 3. The departure coefficient of the upper level is always closer to 1 due to the stronger collisional coupling of the upper levels to the next ionization stage. This results in $b_{up}/b_{lo} > 1$, which combined with the stimulated emission ($h\nu$¡¡kT) drives the line core into emission. For a more detailed description of non-LTE line formation we refer to Sigut & Lester (1996, Sect. 4.4).

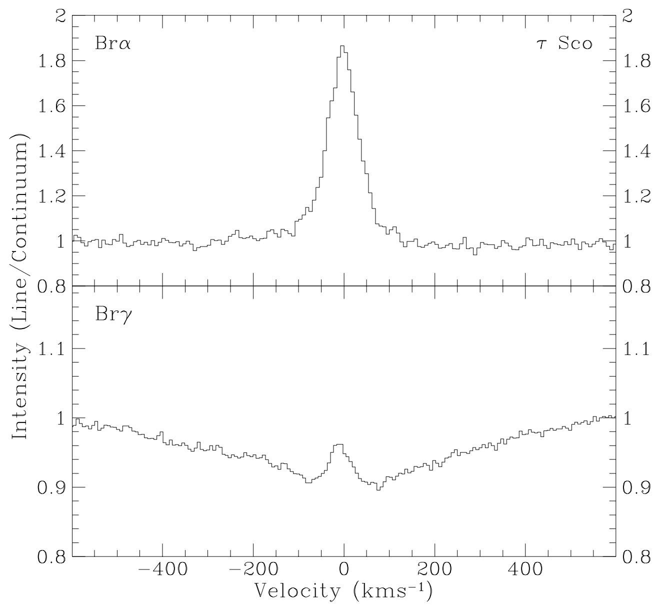

Fig. 1. τ Sco, Brα and Brγ. The velocity scale in this figure and all subsequent ones refers to the center of mass of the star.

Although we do not expect disc formation for the stars rotating more slowly than 200 km s^{-1} for a star with spectral type B2 (Bjorkman & Cassinelli, 1993), some stars in our sample may be rapid rotators with a pole-on orientation. Such stars might give rise to strong HI IR lines without showing any emission in Hα (Zaal et al., 1995).

Three stars in this subset show single-peaked Brα emission features. Two stars, τ Sco and 10 Lac, were already known to have emission in Brα and Brγ (Waters et al., 1993; Murdoch et al., 1994). In a static atmosphere the line is expected to be symmetric and to be at zero velocity in the rest frame of the star. However, in these three cases the emission lines are slightly asymmetric and show an overall negative peak velocity. This might indicate that at the level where non-LTE effects become dominant there is an overall outward directed velocity, i.e. the line is formed in the onset region of a stellar wind.

HD149438 (τ Sco, B0.2V, $v \sin i$ 24 km s^{-1}, Fig. 1): This star was discovered to have emission in Brα and Brγ by Waters et al. (1993). The observations in 1992 showed a strong, single-peaked Brα emission line with a peak line to continuum peak ratio of about 2; the peak velocity of the line was shifted slightly to shorter wavelengths. The Brγ profile of 1992 was rather noisy but a emission feature, with a peak line to continuum ratio of 1.05, was clearly visible.

Both Brackett lines were observed again with improved S/N ratio. Again a slight offset to shorter wavelengths is found for the peak velocity of the emission, although it is less than that in the 1992 data. It is not symmetric; the slope on the short wavelength side is shallower than the slope on the long wavelength side. The wings extend to velocities of about ± 200 km s^{-1}, with the short wavelength wing being stronger than the long wavelength wing. The HeI line (4.049 μm, at –234 km s^{-1} in Fig. 1) is suspected to be in emission and to blend with the short wavelength wing of the Brα emission.

The Brγ spectrum shows strong Stark broadened absorption wings with a weak emission feature in its center. The emission feature peaks at a velocity of –8 km s^{-1}. The Stark wings of Brγ still show sizable slopes at the outer edges of the spectral range, which implies that the EW of the absorption component as given in Table 2 is a lower limit.

In order to compare between the Brα line profiles observed in 1994 and in 1992 we reduced the 1992 data again, in the same way as described in section 2. Because of a better continuum determination the equivalent width given by Waters et al. (1993) has been adjusted from 10 to 14 Å. Compared to 1992 we find that: (1) – the line shape has not change significantly; (2) – the line strength decreased by 4 Å; and (3) – the He I 4.049 μm line is suspected to be in emission in both spectra. The strong asymmetry was not noticed in the 1992 data because of the lower S/N ratio. Furthermore, for both lines the peak velocities have an overall negative value with respect to the photosphere.

τ Sco is a peculiar star. It is a source of X-rays (Swank, 1985; Cassinelli, 1985) with an unusually hard component suggesting the presence of very hot gas ($> 10^7$ K) near the star. The presence of the strong blue-shifted absorption wings in the resonance lines of CIV, SiIV, NV and OVI indicates a mass loss rate of $7\cdot 10^{-9}$ $M_\odot$yr^{-1} at velocities up to 2000 km s^{-1} (Lamers & Rogerson, 1978). These authors also note the presence of long wavelength absorption wings in the lines of OVI and NV, indicating considerable turbulent velocities of about 150 km s^{-1} in the deeper layers of the envelope where the expansion velocity is still small. The presence of the strong blue-shifted absorption wings in the resonance lines of CIV, SiIV and NV are unique for its spectral type and are stronger than those in normal O9V spectra (Walborn et al., 1985). In the optical there are no peculiar features except the strong non-LTE line center found in Hα (Waters et al., 1993). However Smith & Karp (1978) found evidence for some kind of radial motion in the photosphere of τ Sco. The emission found in the Brγ and Brα spectra are mainly due to the non-LTE mechanism as described above. It is not clear if the material seen in OVI and NV by Lamers & Rogerson (1978) is also related to the emission (and asymmetry) seen in the Brα and Brγ spectra.

HD214680 (10 Lac, O9V, $v \sin i$ 31 km s^{-1}, Fig. 2): The Brα spectrum shows a strong emission profile on top on a weak, broad, underlying photospheric absorption as already seen by Murdoch et al. (1994). The Brα peaks at a velocity of –9 km s^{-1}. The emission profile is asymmetric; also an extra absorption component, with a central dip of about 0.9 times the continuum, is visible at about +85 km s^{-1}. This extra absorption can

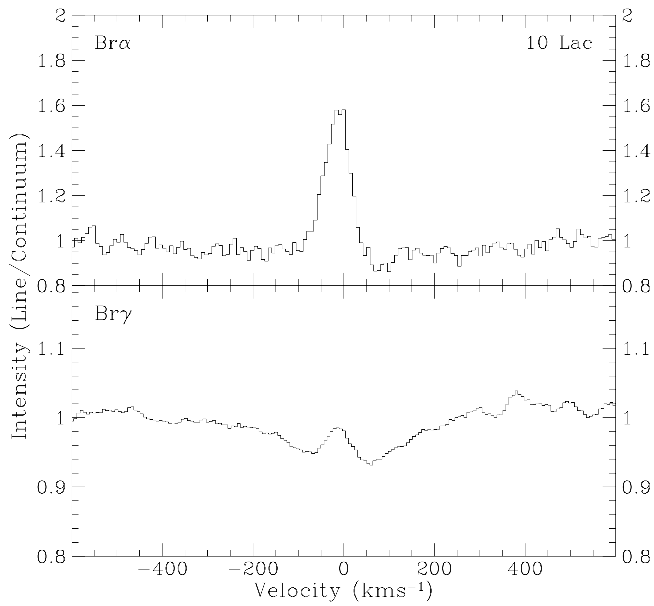

Fig. 2. 10 Lac, Brα and Brγ

also be seen in the Brα spectrum given by Murdoch et al. (1994). The Brγ spectrum closely resembles the Brγ profile of τ Sco; it shows a symmetric absorption component with a weak emission component. Note that the FWZI probably is larger than the spectral coverage, so the EW of the absorption component as given in Table 2 may be a lower limit.

The features seen in the Brγ spectrum at velocities greater than 250 km s^{-1} are artifacts of the data reduction (see Sect. 2). The central emission feature peaks at a velocity of -25 km s^{-1}, shifted even further onto the blue flank than τ Sco.

10 Lac is a well-known main sequence star with weak stellar-wind features in the UV (Underhill, 1975; Kaper et al., 1996). They showed that 10 Lac shows discrete absorption components (DACs). These variations in the UV imply variability in the wind, likely caused by corotating wind structures. They determined that the period of the DACs is $>$ 4 days, i.e. 10 Lac is a slow rotator. This excludes the Brα and Brγ emission is due to a low-density disc. For 10 Lac and τ Sco Murdoch et al. (1994) associate the Brackett emission features with non-LTE effects in the outer parts of the photosphere. The Hα line observed with the echelle spectrograph of the *William Herschell Telescope* (WHT), 1994 (to be published) shows a deep, sharp and symmetric absorption profile which is expected for this slow rotator.

Both Brα and Brγ show Stark broadened absorption wings, formed deeper in the photosphere. This feature together with a central emission component is consistent with that expected from line formation in a non-LTE atmosphere. However, the negative peak velocities might indicate the emission is formed in the onset of the stellar wind. The remarkable, long-wavelength shifted, absorption component (at about + 85 km s^{-1}) seen in the Brα spectrum remains unexplained. It does not seem to be part of the underlying photospheric absorption, which is believed to

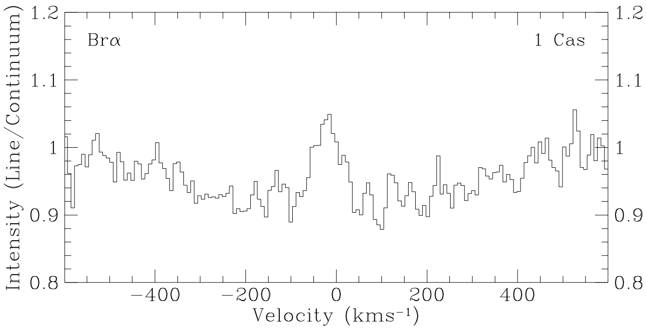

Fig. 3. 1 Cas, Brα

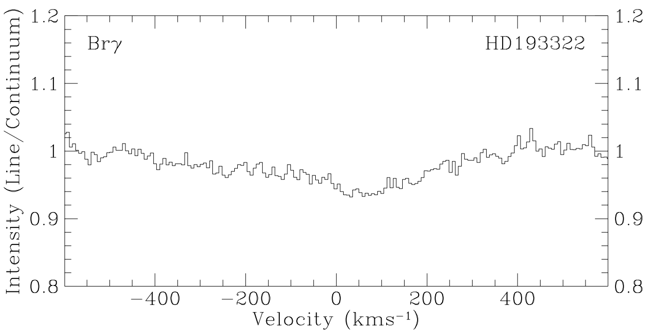

Fig. 4. HD193322, Brγ

be much broader. Perhaps it represents the downward portion of a flow similar to that discussed by Smith & Karp (1978) for τ Sco.

HD218376 (1 Cas, B0.5IV, $v \sin i$ 50 $\mathrm{km\,s^{-1}}$, Fig. 3): The Brα spectrum shows a weak and broad absorption filled in with a relatively broad, central emission peak. The absorption may extend beyond the edges of the observed spectrum. The peak velocity of the emission component is $-22\ \mathrm{km\,s^{-1}}$, its feature is much weaker compared with those in 10 Lac and τ Sco, which is expected because of its lower T_{eff}. The Hα spectrum (WHT 1994, to be published) shows a symmetric deep absorption line profile.

HD193322 (HR7767, O9V:((n)), $v \sin i$ 110: $\mathrm{km\,s^{-1}}$, Fig. 4): This star, is only observed in Brγ, shows a weak broad absorption feature with weak asymmetric features on its wings.

The nature of this star is controversial. Garmany et al. (1980) consider it to be a single star. Whereas Fullerton et al. (1996) find small velocity variations and consider HD193322 to be a double-lined spectroscopic binary. Costero et al. (1984) determined a maximum wind velocity of 1820 $\mathrm{km\,s^{-1}}$ from the resonance lines in the ultraviolet. No infrared excess is found from IR photometry (Castor and Simon, 1983). Hutchings et al. (1979) report that there are two components visible in HeI (5876 Å): a shallow absorption feature and a sharp stronger absorption. They attributed the sharp feature to the presence of a shell.

Although this star has the same spectral type as 10 Lac, it shows no obvious emission features, possibly due to its higher $v \sin i$. The weak asymmetric features would be consistent with a spectroscopic binary interpretation.

3.2. The rapidly rotating B stars

For B stars with $v \sin i > 180\ \mathrm{km\,s^{-1}}$ we may expect to find a double-peaked emission line due to the possible presence of a low-density disc, because Bjorkman & Cassinelli (1993) predict disc formation for these stars (see Sect. 1).

For two of these fast rotators, 2 Vul and HD203938, we find weak double peaked emission in the Brα spectra, which indicates the presence of a low-density disc. These spectra are the first of this kind showing double peaked emission in Brα while the optical Hα is still in absorption. The peak velocities of the emission lines are remarkable; they are lower than expected based on $v \sin i$ of the star. Perhaps the disc is rotating more slowly than expected. Why this might be the case is hard to explain. The difference between the discs found for normal Be stars, which emission does peak on $v \sin i$ of the star, and the discs found here is the disc density, which is a factor of 100 lower. The other fast rotating stars in this set do not show any emission, only broad photospheric absorption lines are present.

Interestingly, we find evidence for low-density discs in the two rapidly rotating B0.5 V stars, but not in the 4 rapidly rotating B2-B3 stars in our sample. Although the sample is quite small, it is useful to compare this to the WCD model, which predict that the frequency of discs peaks at spectral type B2. Such a distribution does not seem to be supported by our observations. However, a larger sample needs to be considered before firm conclusions can be drawn.

The Brα line is quite sensitive to the presence of low-density circumstellar gas. Zaal et al. (1995) showed that for B0 and B2 model stars with discs, Brα emission is detectable at densitties as low as $10^{-13}\ \mathrm{g\,cm^{-3}}$. Such densities are predicted by the WCD model. However, we point out that the model calculations by Zaal et al. (1995) did not use the velocity and density distribution of the WCD model, but used the parameterization introduced by Waters (1986). Model calculations of the Brα line strength using the WCD density and velocity distribution are needed to investigate the possibility to detect these discs in Brα. We expect that the calculations by Zaal et al. (1995) should be fairly representative for the WCD Brα line strengths as well.

Owocki et al. (1996) investigated the effects of non-radial line forces on the formation of a wind-compressed disc around a rapidly rotating B-star. They concluded that non-radial line forces can lead to an effective suppression of the equatorward flow needed to form a WCD. Together with gravity-darkening effects this can even result in a wind geometry that is markedly different than envisioned in the WCD theory, i.e. disc formation cannot be explained by line-driven flow theory only.

For the fast rotating stars we do not find any single peaked emission in the center of the photospheric absorption. This does not imply that these stars do not have non-LTE effects in their outer atmospheres. In some slow rotators, weak, single peaked emission lines are detected. In more rapid rotators we may not see such lines because these weak features are smeared out over

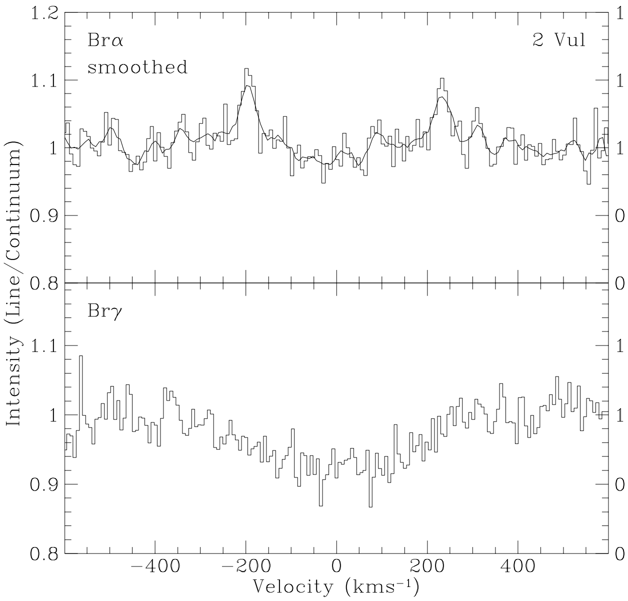

Fig. 5. 2 Vul, Brα and Brγ

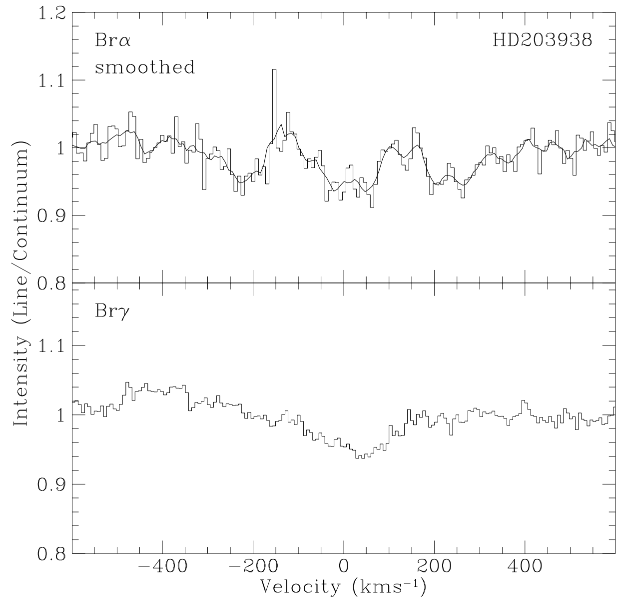

Fig. 6. HD203938, Brα and Brγ

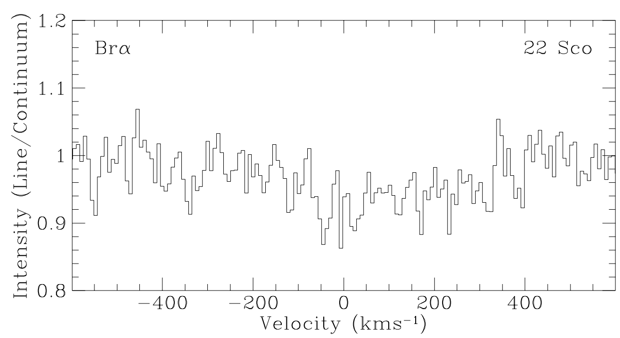

Fig. 7. ζ^4 Lib, Brα and Brγ

a larger frequency range and result only in an overall smaller equivalent width of the expected photospheric absorption line. Non-LTE model calculations are needed to investigate such subtle effects.

HD180968 (2 Vul, B0.5IV, $v \sin i$ 332 km s^{-1}, Fig. 5): The Brα line shows weak, double-peaked emission. It has a I_{peak}/I_{cont} ratio of 1.1, which is a 5$\cdot\sigma$ detection. The Brγ spectrum shows a broad absorption profile. Hα line observation (WHT 1995, to be published) of this star show a triangular line shaped absorption profile.

The Brα line profile shape might indicate that some circumstellar emission is present in this line. The line strength of the weak double-peaked emission agrees with a disc density, ρ_0 of about $8\cdot10^{-14}$ g cm^{-3}, i.e. a factor 100 lower than found for normal Be stars, expected from the WCD of Bjorkman & Cassinelli (1993). However, the disc model (described by Zaal et al., 1995) used to derive this disc density has a different density and velocity distribution compared to the WCD model. This might effect the line strengths and shape of the emission calculated. It remains unexplained why the (peak) velocities found for the double peaked emission in Brα do not agree with $v \sin i$ of the star.

HD203938 (B0.5IV, $v \sin i$ 220 km s^{-1}, Fig. 6): The Brα spectrum shows a weak double-peaked emission on top of a weak broad symmetric absorption. The Brγ spectrum shows an irregular absorption feature. Assuming the presence of a photospheric absorption, we suspect that emission is also present in Brγ at about the same velocities (at about $\pm$ 130 km s^{-1}) as found for the emission in Brα. Also there is evidence of emission near -400 km s^{-1}.

Though this star is a member of multiple system (McAlister, 1989), there is no evidence it is a binary. Sneden et al (1978) found no IR excess flux compared to that expected for a normal B0.5IV star with the given V magnitude. Hα data (WHT 1994, to be published) show a symmetric absorption feature, which looks normal for its spectral type. Like in case of 2 Vul the double-peaked emission can be explained by the presence of a low-density disc. The line strength of the double-peaked emission agrees with a disc density of about $1\cdot10^{-13}$ g cm^{-3}. However, the disc model (described by Zaal et al., 1995) used to derive this disc density has a different density and velocity distribution compared to the WCD model. This might effect the line strengths and shape of the emission calculated. It remains unexplained why the (peak) velocities found for the double peaked emission in Brα do not agree with $v \sin i$ of the star.

HD148605 (22 Sco, B2V, $v \sin i$ 232 km s^{-1}, Fig. 8): The Brα spectrum of this star shows a broad absorption feature. which agrees with other spectra seen for other stars with about the same spectral type and $v \sin i$ (like ζ Lib and 2 Sco).

This star is a MK standard star, for which the HI lines are photospheric. The Hα line profile (JKT 1993, to be published) shows a symmetric absorption feature.

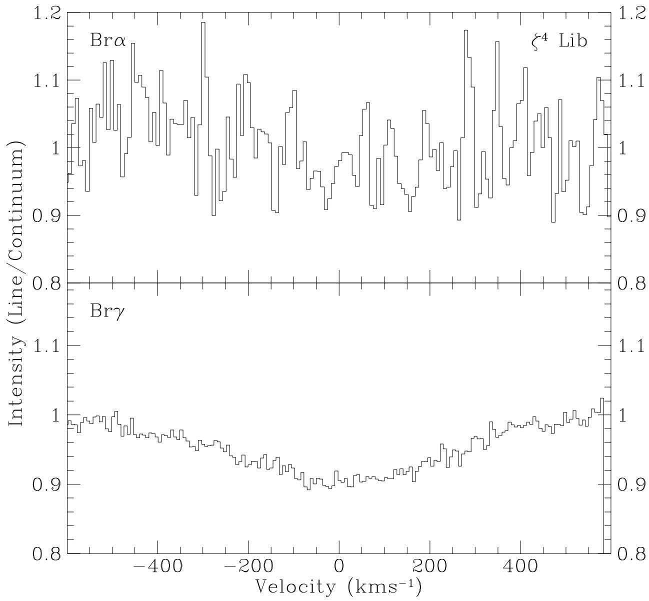

Fig. 8. 22 Sco, Brα

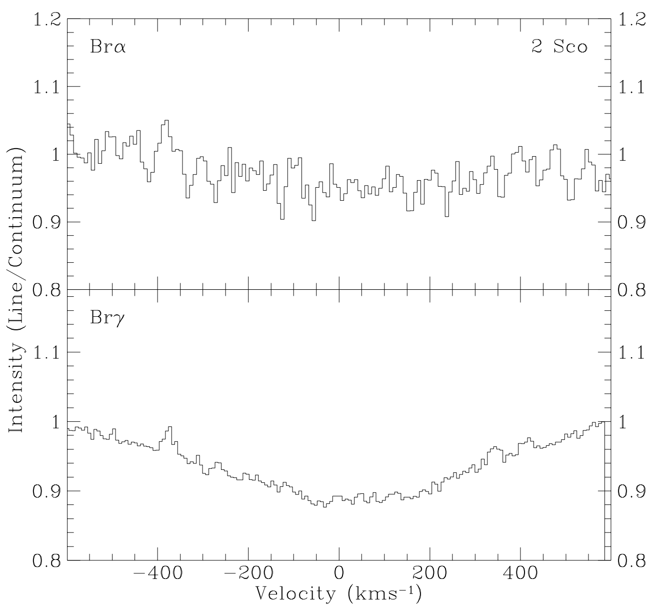

Fig. 9. 2 Sco, Brα and Brγ

HD138485 (ζ^4 Lib, B2Vn, $v \sin i$ 256 km s^{-1}, Fig. 7): The Brα spectrum with its low S/N ratio, does not rule out weak emission feature. The Brγ line shows an broad symmetric absorption. The observed Hα spectrum (*Jacobus Kapteyn Telescope* (JKT) 1993, to be published) shows a symmetric absorption feature.

ζ^4 Lib shows radial velocity variations and is classified as a single-lined spectroscopic binary star which period is believed to be $<$ 6.5 days (Hoof et al., 1963; Levato et al., 1987). It is unresolved by speckle interferometry (McAlister et al., 1987). Neither of the spectra show visible emission features and so the the lines are believed to be photospheric.

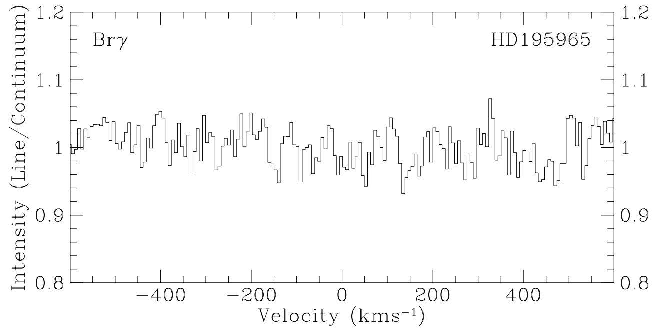

Fig. 10. HD195965, Brγ

HD142114 (2 Sco, B2.5Vn, $v \sin i$ 308 km s^{-1}, Fig. 9): Like ζ Lib, this is a rapidly rotating star which shows a flat Brα profile. The Brγ spectrum shows a broad symmetric absorption. *HD195965* (B0V, $v \sin i > 200$ km s^{-1}, Fig. 10): A featureless Brγ spectrum was found for this star. Although its spectral type is close to the range of types where one expects non-LTE features, no emission is found.

The non-existence of any emission features might indicate that its $v \sin i$, which is unknown, is high. The photospheric lines present in the high-resolution IUE spectrum of HD195965 indicate the $v \sin i$ to be larger than 200 km s^{-1} (microfiche atlas, Bohlin et al., 1994).

3.3. The β Cephei star, θ Oph and the slowly pulsating B star, ι Her

θ Oph belongs to the class of β Cephei stars which are believed to pulsate in p-modes, having periods around 5 hours (Heynderickx, 1992). ι Her seems to show p-modes as well as g-modes (Mathias & Waelkens, 1995), which means it is situated in an instability zone between β Cephei stars and the so-called slowly pulsating B stars (SPBs; Waelkens, 1991). These SPBs (the photometric analogues of the 53 Persei stars) pulsate in many g-modes, each having periods of about 1–3 days. ι Her shows periodic and quasi-periodic changes (on time scales between hours and little more than a day) in its optical line profiles (Mathias & Waelkens, 1995; Smith, 1977). In addition to the periods, the amplitudes also change on timescales of about a month. Mathias & Waelkens (1995) think that the variations in the Doppler heliocentric radial velocity (RV) of ι Her are due to pure atmospheric motions, i.e. they rule out a binary hypothesis. The expected companion has never been observed. Also these stars show an X-ray excess (Grillo et al., 1992), whose origin is not yet clear; it might be due to the shock heated atmosphere or due to the possibility of being in a binary system, although there is no evidence that it is a member of a binary system.

For both of these stars (Fig. 11) we find: (1) Brα emission in the center of an underlying broad photospheric absorption; (2) emission in the HeI line at 4.049 μm. The HeI emission in the spectrum of θ Oph is weaker than in ι Her and due to poorer S/N ratio less obvious. In the spectrum of ι Her the emission has zero velocity in the local standard of rest (RV 11 km s^{-1}, BSC).

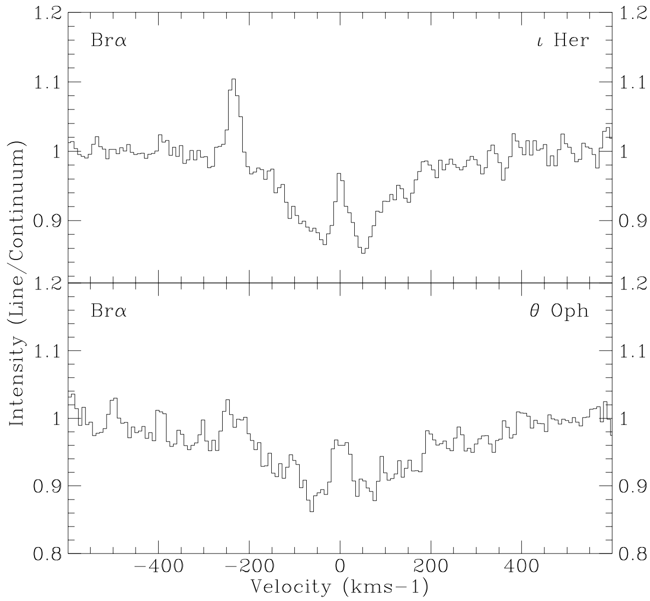

Fig. 11. ι Her and θ Oph, Brα

We used a non-LTE model atmosphere code (Tlusty, Hubeny & Lanz, 1995) to calculate the Brα spectrum of ι Her. These calculations indicate that the Brα emission can be explained by departures from LTE in the regions where the line center is formed (as described in Sect. 3.1). The model did not include enough HeI levels yet to calculate the HeI 4.049 μm line. However, the shape of the HeI 4.049 μm line looks similar to that of the emission seen in Brα. This suggests that also the HeI 4.049 μm line emission originate as a result of the non-LTE mechanism as is the case for HI. The main constraint for such an emission mechanism is the necessity that He is dominantly He^+ and suggests that the degree of ionization in the line forming layers is significantly higher than deeper in the atmosphere for these B2-B3 stars. This may be due to the rapid decrease in density in the outer layers. Detailed non-LTE model atmosphere calculations are needed to determine whether an additional source of heating is required to explain the strength of the HeI line with respect to the HI Brα emission line. We point out that the observed pulsations and X-ray emission suggest that mechanical heating of the outer atmosphere of these stars is occurring.

The extreme line ratio, HeI/Br$\alpha \approx 1$, found for ι Her excludes that the line emission is formed due to recombination. The planetary nebula NGC6572, whose central star has a $T_{eff} \approx 50000$ K (Hyung et al., 1994), shows a line ratio, HeI/Brα of about 0.05. This is close to the maximum theoretical value ($\approx$ 0.04) in case of recombination, considering the fact that 40 percent of the intensity of HeI 5-4 transitions is in the HeI 4.049 μm line and assuming the He over H abundance ratio by number is 0.1 and both, H and He are ionized.

3.4. Others

This group of stars forms a loose subset. All are classified as binaries. 14 Cep (HD209481) is known to be double-lined spectroscopic binary (Morris, 1985). Its Hα spectrum shows a double absorption line (JKT 1993 and WHT 1994, to be published). For two other two cases, η UMa and HD155889, the binary nature is rather unclear. However both these two stars show or have shown remarkable Hα line profiles. The photospheric absorption profile of Hα becomes filled in by a rather flat emission component. For η UMa Bopp et al. (1989) found such an emission component increasing in strength during the period 1986/88. Several Hα observations in the period 1990/95 (Calar Alto and JKT observations, to be published) show that emission component declined and eventually disappeared. The Hα line profile of HD155889 (JKT 1995, to be published) looks similar to the one of η UMa observed by Bopp et al. (1989) during its maximum and is believed to undergo a similar period and might indicate this star is variable.

If the Brα emission in HD155889 is linked to the phenomenon seen in Hα it is different in origin to the emission in 10 Lac, τ Sco and 1 Cas. Because in such a case (non-LTE) the core of the Hα line profile is believed to be formed in a region where the second quantum level is overpopulated and thus would show a stronger central absorption than in case of LTE (see Sect. 3.1). This in conflict with the observed Hα line profile. However, we have to be cautious since the Brα and the Hα observations were not taken simultaneously (the Hα data were taken 4 months later). So non-LTE line formation as an explanation for the Brα emission cannot be ruled out completely.

Bopp et al. (1989) proposed that η UMa is in the transition phase between a B and a Be star. However we do not think this emission can be explained by the presence of a disc, because in this case a double-peaked emission profile would be expected. Instead we propose the emission seen for η UMa and also for HD155889 is due either to the binary nature (tidal interaction) of each system, or to a period of enhanced mass loss. The geometry of the gas causing such an Hα line profile is however unknown.

HD120315 (η UMa, B3V, $v \sin i$ 205 km s^{-1}, Fig. 12): The observed Brα and Brγ spectra show a smooth, symmetric absorption profile. In the Brγ spectrum some residuals, from the strong telluric lines at about $\pm$ 390 km s^{-1} are still visible.

Cassinelli et al. (1994) classify η UMa as a spectroscopic binary, but note the nature of the companion is unknown. The IRAS flux (IRAS Point Source Catalogue, 1988) of 2.9 Jy at 12 μm shows that the star had no infrared excess in that period. The observed flux fits well with the predicted 12 μm magnitude, derived from its V magnitude and color, B–V (Waters et al., 1987), assuming it is a normal B star.

The IR spectra showed no anomalies from that expected for a normal, rapidly rotating B star; the Brα and Brγ line profiles showed no evidence for circumstellar matter.

HD155889 (O9IV, $v \sin i$ 40 km s^{-1}, Fig. 13): The Brα spectrum shows a single peaked emission. No underlying photospheric absorption is visible, consistent with its early spectral type.

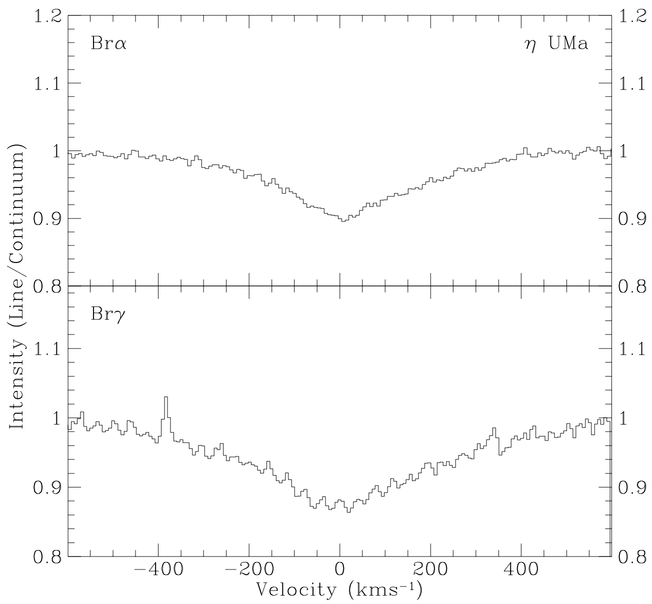

Fig. 12. η Uma, Brα and Brγ

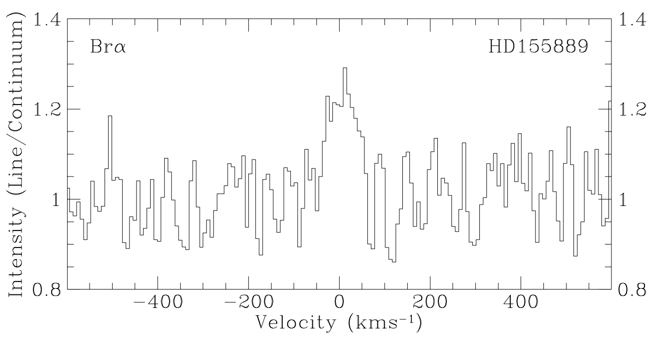

Fig. 13. HD155889, Brα

HD155889 shows an Hα line profile (JKT 1995, to be published) similar in shape as seen in η UMa in 1988 (Bopp et al., 1989). The Brα emission is believed to be related to the emission seen in Hα and thus is believed not to be due the non-LTE effect described in Sect. 3.1. It is not clear at present what the origin of geometry of the circumstellar material is in this star.

HD209481 (14 Cep, O9V:), $v \sin i$ 130: km s^{-1}, Fig. 14): The Brα line shows an irregular emission feature which extends up to a velocity of about $\pm$ 250 km s^{-1}. We are uncertain as to the reality of the line structure seen in the Brα emission profile. The Brγ spectrum shows a rather flat continuum which contains irregular emission superposed on a broad absorption.

14 Cep is known to be a variable star showing ellipsoidal lightvariations, i.e. a non-eclipsing close binary whose components are distorted by their mutual gravitation (Morris, 1985). Its companion is classified as B2V (Merezhin, 1994).

The emission seen in Brα and Brγ cannot be explained in a straightforward way because of the binarity of the star. Either a binary interaction, a high mass loss rate, or a combination of the two might give rise to the Brα emission. The large line

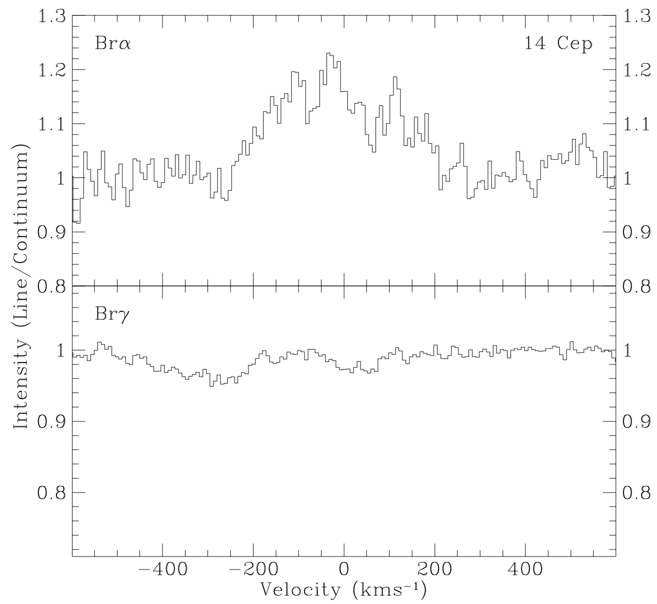

Fig. 14. 14 Cep, Brα

widths seen in the Brα spectrum suggest that the emission may be formed in a region with high turbulent velocities. Brα shows emission while Hα does not. This is not expected if the Brα emission is due to colliding winds. This can be explained by considering that the observations of Brα and Hα (WHT 1994) are not simultaneously taken and that 14 Cep is highly variable.

4. Conclusions

The surprisingly large number of stars with Brα in emission while Hα was in absorption shows that the HI IR lines have the potential to reveal much information about the outer parts of the stellar atmosphere. There are three reasons for this.

The first and most important one is that the HI IR lines can go into emission as a result of non-LTE effects in the atmosphere of an O or early-B star (Murdoch et al., 1994). For the four slow-rotating early-type stars (earlier than B1) investigated, three showed a single peaked emission feature, while Hα was in absorption (Sect. 3.1). For three stars τ Sco, 10 Lac, and 1 Cas, which show emission due to a non-LTE effect, the peak of the emission is shifted slightly to shorter wavelengths. This may imply that the line is formed in a region where the stellar wind begins, so that emission, shifted to shorter wavelengths from these regions, is added to the photospheric non-LTE emission.

In the spectra of two β Cephei stars, ι Her and θ Oph, Brα emission and HeI (4.049 μm) line emission is found. However the EW of these emission features is small (0.5 Å) it is prominent due to the fact that these stars have a very low $v \sin i$, especially θ Oph ($v \sin i$ = 11 km s^{-1}). Non-LTE model calculations (Tlusty, Hubeny & Lanz, 1995) show that the emission in the line center of Brα is due to the departures from LTE in the line forming regions as is the case for the HI IR lines of the late-O and early-B stars. No sizable velocity shift is found for the Brα emission seen in ι Her. The shape of the HeI 4.049 μm emission resembles the the shape of the emission seen in Brα and suggests that the HeI emission is also a result of departures from non-LTE in the line forming regions. This would imply that the degree of ionization in the line forming regions is much higher than deeper in the atmosphere for these B2-B3 stars. It is not clear whether additional mechanical heating of the outer layers of these pulsating B stars is required to explain the HeI line strength.

The second reason is the high sensitivity of the HI IR lines to the presence of circumstellar material. Although the HI IR lines are weaker than those in the optical ($A_{n,m} \propto \nu$), the line to continuum ratio can be larger because of the steep, underlying photospheric continuum in the infrared ($\propto \nu^2$). This will continue up to the point where free-free and free-bound processes start to contribute significantly to the continuum; at lower frequencies the line to continuum ratio will stabilize (Zaal et al., 1995). Of the six rapidly rotating stars observed, two possibly show weak, double-peaked emission (Sect. 3.2). It is however remarkable that the emission is present at lower velocities than expected based on the $v \sin i$ of the star.

Lastly, a particular star with HI IR line emission might be a member of a binary system. A good example is the star 14 Cep, which shows strong Brα emission. However, it is unclear in this case whether the emission is atmospheric or arises as a result of the presence of the companion, because the complexity of the system makes it difficult to interpret the spectral features.

For the rapidly rotating stars we find two cases (2 Vul and HD203938) for which we find weak double peaked Brα emission in the Brα spectra. These two stars probably have low-density discs which are apparent only in the infrared HI lines (Zaal et al., 1995). The emission seen in these spectra shows up at lower velocities than expected for their $v \sin i$. It is remarkable that within the set of 6 fast rotating stars the double peaked emission is found for the stars with spectral type B0.5V-IV and no double peaked emission is found for the stars with spectral type B2-3. This is in contrast with what Bjorkman & Cassinelli (1993) expect for their WCD model; they find a maximum probability of disc formation around spectral type B2. We plan to perform new disc model calculations which include the density and velocity structure within the disc as given by Bjorkman & Cassinelli (1993). This, together with the observed Brα spectra, will put constraints on the disc density.

We intend to use a non-LTE code (Hubeny & Lanz, 1995) to predict line profiles and to study wind properties by comparing the expected photospheric line profiles with observed spectra. We plan to consider both Hα and the HI IR lines. Also we will enlarge the number of levels taken into account for HI and HeI in the model calculations. We will include more HI levels to study the dependency of the departures coefficients (and thus the line emission line strengths) on the number of HI levels included and we will include more HeI levels in order to study the HeI 4.049 μm line strength behavior, especially for the β Cephei stars. Detailed non-LTE model atmosphere calculations are needed to determine whether an additional source of heating is required to explain the strength of the HeI line with respect to the HI Brα emission line. These results will be published in a subsequent paper.

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