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High-resolution spectroscopy of Vega-like stars – II. Age indicators, activity and circumstellar gas

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ABSTRACT

We have completed a high-resolution optical study of 14 stars classified as Vega-like, having an IR excess attributable to dust emission.

Surface lithium abundances were measured for the four G- and K-type stars of the sample, to test the suggestion that these Vega-like stars are intermediate in evolutionary state between pre-main-sequence objects and established main-sequence stars. Abundances ranged from a very high value in the G5e star HD 143006, implying a very low age of only 1 Myr, to below the limit of measurement for the K2V star HD 23362, which we conclude to be already well established on the main sequence.

The emission-line characteristics of all the stars in our sample were studied to compare with those seen in the classical pre-main-sequence Herbig Ae/Be (HAeBe) stars and T Tauri stars. Activity levels ranged from stars showing little or no activity, such as HD 23362, to those exhibiting extensive activity, such as the A9/F0Ve star HD 144432, which showed distinctive P Cyg profiles in its spectrum, and HD 143006, which is young enough to be included in the T Tauri class of stars. The A2/3e star HD 35187 shows evidence of variability in its Hα and He I λ5876 lines, with four other A-type stars in our sample also showing evidence of He I λ5876 activity in the form of emission or absorption. We interpret the excess absorption and/or emission in the λ5876 line as providing direct evidence for ongoing accretion activity on these systems. We find that the emission characteristics of the Hα, Na I D, He I and Ca II K lines are not significantly different from those of HAeBe stars and T Tauri stars. Some of our sample have also been previously classified as pre-main-sequence or candidate pre-main-sequence stars, which would seem to suggest that there is no distinct boundary between Vega-like stars and the HAeBe and T Tauri stars. The surface gravities of the A- and F-type stars in our sample imply that they have already reached the main sequence, consistent with the short time-scales to reach the main sequence predicted for stars of their mass and the fact that they are not located close to star formation regions. On the other hand, the ages derived for the three emission-line G- and K-type stars in our sample imply that they have probably not yet reached the main sequence. It is likely that these emission-line Vega-like stars represent the intermediate stage between classical pre-main-sequence stars with 'dusty' IR excesses and stars that are well established on the main sequence.

We also studied our sample for evidence of optical circumstellar gas absorption features. Of the 14 stars, seven show evidence for narrow absorption lines in their spectra. Most of these appear to be of interstellar origin. One of these stars, HD 144432, has a narrow absorption component in the absorption trough of its Na I D P Cyg profile, at a heliocentric velocity of $-91\ \mathrm{km\ s^{-1}}$, which excludes an interstellar origin and therefore more likely originates in its circumstellar environment. We also detect narrow absorption lines in the spectrum of HD 158643 (51 Oph) arising from excited-state Fe II lines, which can only come from the circumstellar environment of the star.

Key words: techniques: spectroscopic – circumstellar matter – stars: activity – stars: evolution.

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1 INTRODUCTION

This is the second of two papers studying the optical spectra of Vega-like stars. In Paper I (Dunkin, Barlow & Ryan 1997a), we derived stellar parameters and photospheric abundances for a sample of 14 Vega-like main-sequence stars. There have been suggestions that Vega-like stars represent an evolutionary stage between pre-main-sequence stars and main-sequence stars like the Sun (Aumann et al. 1984; Sylvester et al. 1996 and references therein) and we compare here several properties of the stars in our sample with those of pre-main-sequence objects. In particular, the lithium λ6708 line is used in Section 2 to estimate ages for the later type stars in our sample, while in Section 3 we look for evidence of youthful activity in the stars in our sample, as revealed by emission in the lines of Hα, Na I D and Ca II K, amongst others.

The presence of dust in the circumstellar environment of a Vega-like star should also imply the presence of some gas in the region. Searches for gas such as molecular CO have been carried out by Zuckerman, Forveille & Kastner (1995) and Dent et al. (1995). The properties of various circumstellar absorption lines in the spectrum of β Pic have been studied in detail (Beust, Vidal-Madjar & Ferlet 1991 and references therein). Spectacular variability in the Ca II K line is found, suggesting movement of gaseous material in the near environment of β Pic. Beust et al. proposed that the variability was caused by star-grazing comets being perturbed by a planet on an eccentric orbit around the star. As well as Vega-like stars, other stars associated with circumstellar material (shell stars and some λ Boo stars) have also been studied for evidence of circumstellar gaseous material in their optical spectra (Lagrange-Henri et al. 1990, hereafter LH90; Holweger & Rentzsch-Holm 1995). In Section 4 we search for evidence of circumstellar material around our programme Vega-like stars and compare our results, where possible, with previously published data.

The data used here are the same as in Paper I, comprising spectra from the UCL Echelle Spectrograph at the 3.9-m Anglo-Australian Telescope (AAT), with resolving powers of ~44 000, together with spectra having a lower resolving power of 15 000, obtained with the 2.1-m telescope of the Observatorio Astronomico National (OAN) of Mexico, using the ROESC echelle spectrograph. The wavelength coverage of the OAN data was 4100–8700 Å, complete for 4100–6600 Å, and with gaps between the orders from 6600 Å onwards. The AAT spectra were taken at two wavelength settings. The blue spectra gave complete coverage from 3800 to 4960 Å, and the red spectra incomplete coverage between 5260 and 9200 Å. More details of the observations can be found in Paper I; the stars observed are listed here in Table 1.

2 THE Li I 6708-Å LINE IN THE G- AND K-TYPE STARS

The Li I 6707.81-Å resonance line is the most easily visible line of Li I in the optical spectrum of unevolved cool stars, and is prominent in the spectra of some of the later type stars of our sample.

Studies of lithium have great importance in understanding the structure and evolutionary history of stars, despite it being difficult to detect. The abundance of lithium observed in the photospheres of stars is a potential indicator of age (Herbig 1965), with lithium depletion resulting from internal convection, where the lithium is transported to inner regions of the stars and subsequently destroyed at $T > 2 \times 10^6$ K.

The detection of lithium in a late-type star with an IR excess would be significant since a high lithium abundance could imply that the star is very young and perhaps still in its pre-main-sequence

Table 1. Stars observed.

Star HD	SAO	Name	L_{IR}/L_*†	Spec. Type	v sin$i$ (km s^{-1})	$V_\odot$ (km s^{-1})	Date of obs.	Site
23362	111388		7.9×10^{-4}	K2V	-	-	26 Sept 93	OAN
35187	77144		0.14	A2/3 IV/Ve	93±5	25±7	26 Sept 93	OAN
98800	179815		0.084	K5Ve	5*	12.5±0.4	25 Feb 94	AAT
123160	158350		4.4×10^{-3}	G5V	9±1	−6.4±0.4	20 June 94	AAT
135344	206462		0.64	F4Ve	69±3	−3±3	25 Feb 94	AAT
139614	226057		0.39	A7Ve	24±1	3±1	20 June 94	AAT
141569	140789		8.4×10^{-3}	A0Ve	236±9	−6±5	20 June 94	AAT
142666	183956		0.34	A8Ve	70±2	3±1	20 June 94	AAT
143006	183986		0.56	G5Ve	12±2	−0.9±0.3	20 June 94	AAT
144432	184124		0.48	(A9/F0)Ve	74±2	2±2	20 June 94	AAT
158643	185470	51 Oph	0.028	B9.5Ve	267±5	−20±3	20 June 94	AAT
169142	186777		0.088	A5Ve	55±2	−3±2	17 June 94	AAT
Spectral Standards								
161868	122754	γ Oph	4.2×10^{-5}	A0V	214±3		20 June 94	AAT
187462	87766	α Aql	—	A7V	189±6		20 June 94	AAT
198001	144810	ϵ Aqr	—	A1V	95±5		20 June 94	AAT
200499	189986	22 Cap	—	A5V	52±2		16 June 94	AAT
214850	108094		—	G3V	-		16 June 94	AAT
216956	191524	α PsA	8×10^{-5}	A3V	88±2		16 June 94	AAT

See Paper I for derivation of spectral class for these stars and for their v sin$i$ and $V_\odot$ determination.
*From Soderblom et al. (1996).
†From Sylvester et al. (1996) and Paper I.

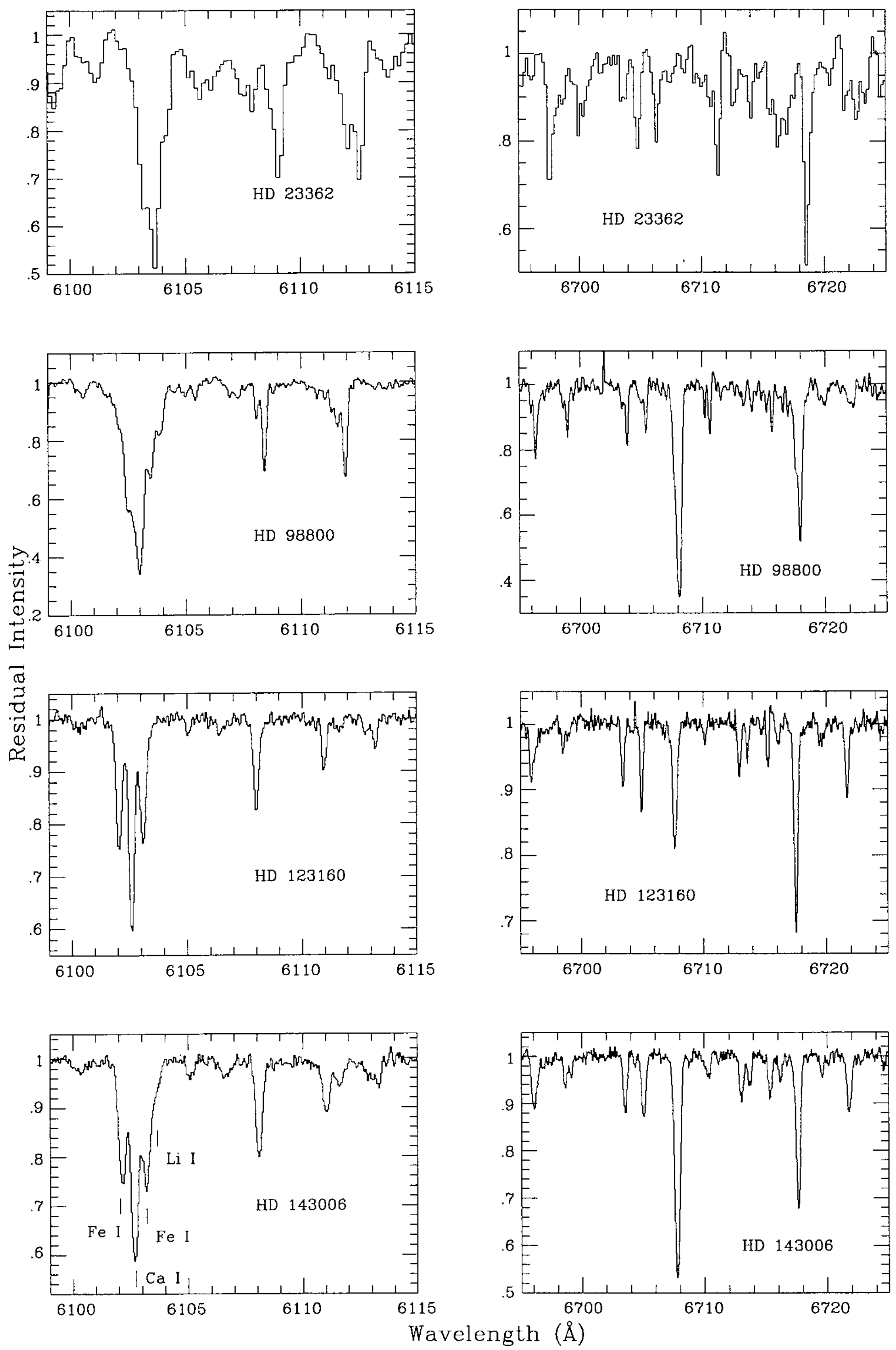

Figure 1. The two lithium-line regions discussed in the text. The left-hand plots show the region containing the Li I λ6103 line. This region is dominated by lines of Fe I and Ca I, with Li contributing only weakly to the overall profile. Li can just be seen in the spectra of HD 143006 and 98800, which have very strong lines at 6708 Å, but is barely distinguishable from the continuum and Fe I line in HD 123160, which does not have such a prominent feature at 6708 Å. The right-hand plots show the Li I λ6708 line, which was used to determine the abundances used to calibrate the ages of the stars. Wavelengths have not been corrected for the small radial velocities of the stars.

stage of evolution. However, Pallavicini, Cerruti-Sola & Duncan (1987) note that a high lithium content is a necessary but not sufficient criterion for a star to be young; for the same spectral type, one should expect to see other indications of youth, such as enhanced chromospheric activity and rapid rotation, in order to be certain of the youth of the star. The $v \sin i$ values of the stars were derived in Paper I and are listed in Table 1 here, while the level of activity of the stars is discussed in more detail in Section 3 of the current paper.

It has been suggested recently that the 6708-Å line consistently overestimates the true abundance of lithium (Balachandran & Carr

Table 2. Equivalent widths and the corresponding Li abundances derived from the λ6708 Li I line. The equivalent widths for HD 98800 are discussed in the text. The solar abundance of Li is 1.16 dex (Anders & Grevesse 1989), on a scale where log N(H) = 12.00.

Star		Sp	T_{eff}(K)	log g	v sin$i$	W_λ(mÅ)		Log N(Li)		
HD	SAO				km s^{-1}	Li I	Fe I	This work	Padgett (1990)	Soderblom et al. (1993)
123160	158350	G5V	5570	4.5	9	78	3	2.31	2.21	2.25
143006	183986	G5Ve	5570	4.5	12	241	5	3.46	3.25	3.28
23362	111388	K2V	5010	4.5	-	< 15	-	<0.87	-	<0.85
98800	179815	K5Ve	4510 (Aa)	4.5	5*	399	20†	2.91	2.81	2.97
			4250 (Ba)			373	20†	2.35	2.1	2.50

*v sin$i$ value for HD 98800 taken from Soderblom et al. (1996).
†value assumed. See text for details.

1994; Houdebine & Doyle 1994), with the subordinate line at 6103 Å being favoured as a more reliable indicator of abundance. The 6103.65-Å line is much harder to detect, having close Fe I and Ca I neighbours (see Fig. 1). Due to this proximity and the blended nature of these lines, we decided to work only with the line at 6708 Å.

The 2s–2p ^{7}Li I resonance line has two fine-structure components (6707.761 and 6707.912 Å, log gf = 1 and 0.5 respectively), as does the line of ^{6}Li, shifted 0.16 Å redward, which together make up the 6708-Å feature. In addition, this feature has a close Fe I neighbour at λ6707.44, which in our spectra has not been completely resolved. However, in most cases there is enough structure visible within the Li I profile for an accurate determination of the contribution of the Fe I line to the total equivalent width to be made.

2.1 Analysis

The equivalent widths of the lines were determined via multiple Gaussian fits to the data using the DIPSO package (Howarth & Murray 1988). Only one Gaussian was required to produce an accurate fit to the line of lithium, and one for the iron line. Allowing for the lithium multiplet components made no significant difference to the equivalent widths derived from our data. The errors on the equivalent widths, and hence the abundances, were derived by taking extremes of continuum normalization as described in Paper I and redetermining the equivalent width. As before, this was found to be the largest source of error in our analysis.

The Li abundances were derived using the spectrum synthesis code described in Cottrell & Norris (1978), using the line list assembled by Anderson, Gustafsson & Lambert (1984). We could compare the values obtained from the synthesis with the empirical calibrations of Padgett (1990) and Soderblom et al. (1993). The results are shown in Table 2. Good agreement is found for all stars except for a slight discrepancy for HD 143006. We have used the lower Li abundance based on the Padgett and Soderblom calibrations, since those two calibrations agree; it is the more conservative of the two values and so should produce an upper limit for the age of the star.

2.2 Discussion

HD 98800 has been extensively studied in terms of its age and multiplicity (Fekel & Bopp 1993; Torres et al. 1995; Soderblom et al. 1996). Fekel & Bopp (1993) reported detailed optical studies of HD 98800, including the 6708-Å line of lithium. The total equivalent width they found for the blend (410 mÅ) is slightly larger than the 395 mÅ found here, as is the value of 430 mÅ found by Soderblom et al. (1996), but larger than the value of 370 mÅ found by Gregorio-Hetem et al. (1992). It is not clear from the latter work whether the measurement is of the Li line alone, or of the blend of the Li line and its close Fe I neighbour. Identifying the contribution of the Fe line to this blend is sometimes difficult, especially in cases such as HD 98800 where the two lines are closely blended. Pallavicini et al. (1987) measured the equivalent widths of Li and Fe lines for stars down to K3V spectral type, showing that the Fe I contribution increased from F8 to K3, with their K3V star having an Fe I λ6707.4 equivalent width of 13 mÅ. Pallavicini et al. (1992) use measurements of the Li and Fe lines in several narrow-lined Population I stars to determine the contribution of the Fe line to the 6708 blend in stars whose lines are blended together. For their example of a K5V star (the same spectral type as HD 98800) with blended lines, they estimated the equivalent width of Fe I in the blend to be 16 mÅ, but their equivalent width measurement for the observed blend had an upper limit of only 9 mÅ. This confusing issue highlights the fact that we cannot accurately determine the true contribution to the blend by the Fe I λ6707.4 line. Fekel & Bopp (1993) adopted an Fe I equivalent width of 20 mÅ on the strength of the work of Pallavicini, Randich & Giampapa (1992). Since this appears to be an upper limit to the Fe I contribution, we too adopt this value, but note that it could easily be smaller, giving a slightly larger equivalent width for the Li line, and hence a slightly lower age for the star. For HD 98800, this implies an equivalent width for the Li I line alone of 375 mÅ in our spectrum, in good agreement with Gregorio-Hetem et al. (1992), should their measurement be for the Li I line only, and only slightly less than the 390 mÅ found by Fekel & Bopp (1993) after their correction for the Fe line.

The most likely cause of the observed Li line broadening in the case of HD 98800 (Fig. 1) is line blending caused by the stellar multiplicity. HD 98800 is a member of a four-star system, being a well-known visual binary with a separation of less than 1 arcsec, with each visual component (Aa and Ba) being a spectroscopic binary (Aa+Ab and Ba+Bb: Torres et al. 1995). The lines from the two brightest components of the system (Aa and Ba) have been resolved in our spectrum (Fig. 2), exhibiting a separation of approximately 0.33 Å for other lines in the 6708-Å region. This is just the value expected (14.7 km s^{-1}) from the predicted velocity separation of components Aa and Ba at the time of our observation, using table 1 of Torres et al. (1995). Although the components are resolved in the weaker lines, the lithium line is very strong, and remains unresolved. The strong asymmetry in the line suggests that component Ba also has a significant Li content (confirmed by

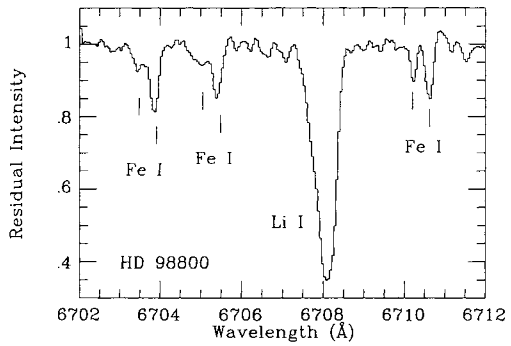

Figure 2. The Li 6708-Å region of HD 98800. The lines of Fe I from stars Aa and Ba have clearly been resolved (components indicated by tick marks), whereas the stronger component of Li I remains blended. There is, however, a strong asymmetry in the Li line, indicating that the secondary star Ba has a significant abundance of lithium in its photosphere.

Soderblom et al. 1996), which is contributing to the overall blend. We can produce a crude, two-component Gaussian fit to the lithium line, to obtain upper limits on the lithium content from the primary and secondary sources. Using this two-component fit to the line, the apparent equivalent widths for components Aa and Ba are 238 and 165 mÅ respectively. Allowing for the diluting effect of Ba (using proportions of 57 per cent for Aa and 43 per cent for Ba), we calculate the intrinsic equivalent widths to be 419 mÅ for Aa and 393 mÅ for Ba. Allowing for a 20-mÅ contribution by the Fe I line, this translates to an equivalent width of 399 mÅ for Aa and 373 mÅ for Ba. Soderblom et al. (1996) found intrinsic equivalent widths of 425 mÅ for Aa and 335 mÅ for Ba. Our values for Aa are similar, but the discrepancy between the Ba values is probably due to the fact that Soderblom et al. were also able to separate out the contribution of the Bb component. Soderblom et al. did not correct for the Fe I component in their quoted equivalent widths (Soderblom, private communication). Assuming a 20-mÅ equivalent width for the Fe I, this would make their equivalent widths 405 mÅ for Aa and 315 mÅ for Ba, bringing our values more in line with those of Soderblom et al. Our intrinsic equivalent widths imply abundances of log$N$(Li) = 2.91 and 2.35 at $T_{\rm eff}$s of 4500 K for Aa and 4250 K for Ba respectively (Soderblom et al. 1996). These abundances are higher than those found by Soderblom et al. (1993) for main-sequence stars of similar spectral type in the Pleiades (age ~70 Myr), but below the values found by Padgett (1990) for the Taurus–Auriga clouds, where the ages of the pre-main-sequence T Tauri stars have been estimated to be 1 Myr by Kenyon et al. (1990). This would imply that the age of HD 98800 lies between these two values, arguing for a very low age for the system.

Using the same argument for the G5Ve star HD 143006, and its derived Li abundance of log$N$(Li) = 3.27 dex, we find that it is bracketed by stars of the Taurus–Auriga group studied by Padgett (1990). The age of this group was estimated to be 1 Myr by Kenyon et al. (1990), and it is therefore likely that the age of HD 143006 is close to this figure. The high abundance of lithium in HD 143006 is also consistent with that found in T Tauri stars (Maguzzu, Rebolo & Pavlenko 1992) and, as discussed in Section 3, HD 143006 is most likely a member of the T Tauri class.

The abundance of lithium in the G5V star HD 123160, log$N$(Li) = 2.31, is consistent with those found for stars of similar spectral type in the Pleiades by Soderblom et al. (1993), implying that HD 123160 is around 70 Myr old. The results for HD 123160 and 143006 fit in well with the results from the activity indicators discussed in Section 3. There we find that HD 143006 is one of the most active stars in the sample while HD 123160 is the least active, with the exception of HD 23362. HD 23362 shows no detectable Li I line (Fig. 1) at 6708 Å, with the upper limit implying a significant depletion of Li in this star (Table 2). The absence of lithium suggests an age significantly older than that associated with young main-sequence stars. We therefore conclude that HD 23362 is more evolved on the main sequence than the rest of our sample.

3 EMISSION-LINE CHARACTERISTICS

From their IR properties and spectral types, the stars in our sample have been classified as Vega-like main-sequence objects. The very large IR excesses associated with a number of these Vega-like stars (Sylvester et al. 1996) suggest that they may be very young and so it seems natural to compare some of the characteristics observed in their optical spectra with those of other young objects, namely the pre-main-sequence HAeBe stars and their lower mass counterparts, the T Tauri stars. In this section we study the emission-line characteristics of our complete sample of stars and highlight similarities (where appropriate) with the above pre-main-sequence objects.

3.1 The earlier type stars – B9.5 to A9

The closest spectroscopic similarities to the earlier type Vega-like stars are exhibited by the class of Herbig Ae/Be (HAeBe) stars. Herbig (1960) first surmised that 'Be and Ae stars associated with nebulosity' were intermediate-mass objects in their pre-main-sequence stage of evolution. He laid down criteria with which to select other candidates for this class: (a) the stars must be earlier than F0, (b) they must exhibit emission lines in their spectra, (c) they must lie in an obscured region, and (d) they must illuminate a reflection nebula in their vicinity. Criterion (a) eliminates lower mass stars, hence their definition as intermediate-mass objects. Criterion (c) is considered an indication of youth, since the stars have not had time to escape their birthplace. Criterion (d) distinguishes those stars truly associated with the obscured region and those simply in its line of sight. Nowadays, criterion (d) is not strictly applied, but still gives reassurance. Criterion (b), the presence of emission lines, was also considered as a criterion of youth since emission lines had previously been observed in the T Tauri class of stars (see Section 3.2).

Emission lines in the spectra of HAeBe stars have been extensively studied (see Catala 1989 for a general review). In particular, emission lines of Hα, Na I D, He I 5876 Å (e.g Finkenzeller & Mundt 1984; Böhm & Catala 1995; Grady et al. 1996), [O I] 6300 Å (e.g. Finkenzeller & Mundt 1984), and the Ca II IR triplet (e.g. Böhm & Catala 1995) have been studied as indicators of activity and winds. Finkenzeller & Mundt (1984, hereafter FM84) conducted an extensive survey of the Hα, Na I D and He I profiles of 57 HAeBe or HAeBe candidates. They found that the Hα profiles could be split into three categories: single-peaked emission profiles (s), double-peaked profiles (d) and those exhibiting P Cyg profiles (p). Of their sample, 25 per cent were (s), 50 per cent were (d) and 20 per cent were (p). The remaining 5 per cent had peculiar profiles and could not be placed into any of the above categories. Of the nine B and A stars in our sample that show IR excesses, two show no emission lines (the spectral standards, α PsA and γ Oph), four show double-peaked structures, two show single-peaked profiles and the remaining star (HD 144432) shows a P Cyg profile in its Hα line [Fig. 3(e)i]. The actual cause of the velocity structure remains uncertain. A P Cyg profile gives a definite indication of outflow, but

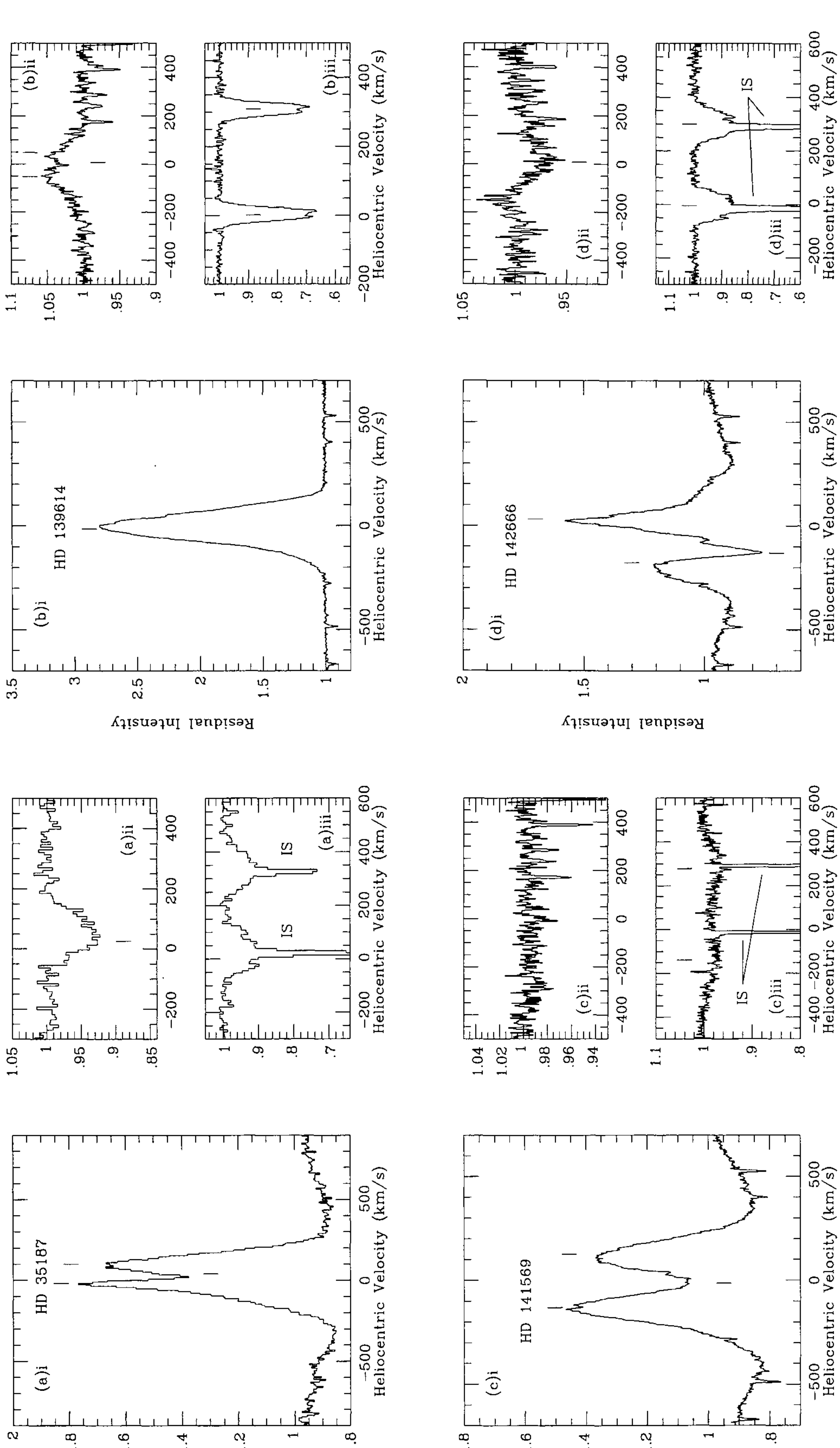

Figure 3. Indications of activity in the lines of Hα (i), He I λ5876 (ii) and Na D (iii), for (a) HD 35187 (A2/3 IV/Ve), (b) HD 139614 (A7Ve), (c) HD 141569 (A0Ve) and (d) HD 142666 (A8Ve). Tick marks correspond to the velocities tabulated in Table 4. Velocities have not been corrected for the radial velocity of the star.

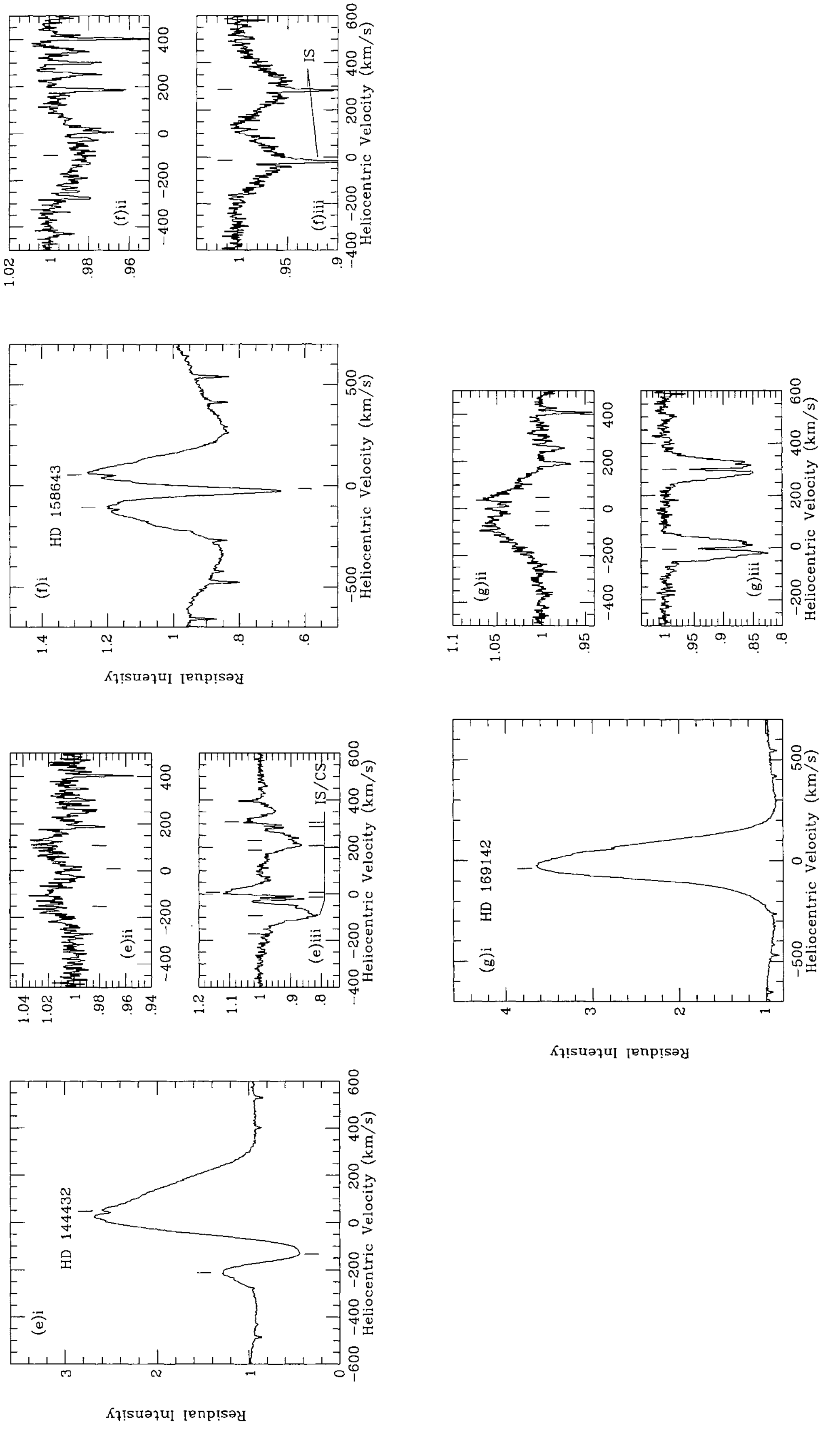

Figure 3 – *continued*. Indications of activity in the lines of Hα (i), He I λ5876 (ii) and Na D (iii), for (e) HD 144432 (A9/F0Ve), (f) HD 158643 (51 Oph, B9.5Ve) and (g) HD 196142 (A5Ve). Tick marks correspond to the velocities tabulated in Table 4. Velocities have not been corrected for the radial velocity of the star.

Table 3. Emission-line characteristics of the earlier type stars in our sample and their properties.

Star HD	Star SAO	Spectral Type	Hα Type[1]	Hα Peaks[2]	Na I D Type[1]	He I Type[1]	Ca Triplet Type[1]
35187	77144	A2/3 IV/Ve	d	V>R	abs	abs	—
139614	226057	A7Ve	s	—	core	d	—
141569	140789	A0Ve	d	V>R	abs	—	—
142666	183956	A8Ve	d	V<R	—	abs	—
144432	184124	A9/F0Ve	p	—	p	d	p
158643	185470	B9.5Ve	d	V<R	abs	—	d
169142	186777	A5Ve	s	—	core	d	—

Notes to Table 3.

1. d – double peak, s – single peak, p – P Cyg profile, core – core emission with peak not exceeding the surrounding continuum, abs – absorption in excess of that expected for its spectral type.

2. V and R refer to the violet and red peaks of the double-peaked emission respectively. This column indicates which of the peaks is higher relative to the surrounding continuum than the other.

Table 4. Heliocentric velocities (in km s^{-1}) of line components shown in Fig. 3. The velocities correspond to the tick marks shown in that figure. Errors on the measurements are typically ±1.5 km s^{-1}. The measurements for $V_{\odot}$ come from an analysis of several lines in the 4100–4500 Å region.

Star HD	Star SAO	$V_{\odot}$	Hα			He I			Na D_2		
35187	77144	25±7	−48.5	+27.9	+73.7	+21.5			−9.3		
139614	226057	3±3	−0.4			−58.3	−7.2	+31.1	+2.7		
141569	140789	−6±5	−135.4	−9.0	+107.1				−148.4		
142666	183956	3±1	−190.0	−126.7	+22.6	+13.6			−6.9		
144432	184124	2±2	−212.8	−126.6	+30.2	−119.3	−12.0	+113.8	−159.5	−80.4	+3.7
158643	185470	−20±3	−114.8	−26.7	+53.6	−90.5			−23.3		
169142	186777	−3±2	−23.3			−67.4	−25.2	+40.1	−3.1		

single and double peaks have a more uncertain origin, although the double-peak structure has been described in terms of a rotating, expanding envelope seen closer to edge-on than pole-on (Marlborough 1969, 1970). FM84 noted that stars that showed single- or double-peaked emission in the Hα line rarely exhibited Na I D emission. Contrary to this we find that the two stars with single-peaked Hα profiles both show emission in the core of the sodium doublet. Our sample is far from complete, and the fact that both of our double-peaked Hα stars show sodium emission may be a fortuitous coincidence. We also note that the resolution of FM84 was lower than ours. By degrading our data to their resolution of 0.35 Å (at Hα) we found that the Na I D emission of HD 139614 was undetectable, but that of HD 169142 remained clearly visible. HAeBe stars often show signs of variability, sometimes dramatic and on a short time-scale. Do the Vega-like stars also show similar emission-line variability? Very few optical spectra of these stars have been published and we are therefore unable to determine the nature of any emission-line variability present in most of our stars. Further observation of lines such as Hα and the sodium doublet are essential if this question is to be answered. It may well shed light on the differences, or instead show even greater similarities, between the HAeBe stars and the Vega-like stars. The question of circumstellar line variability, as observed in the Vega-like prototype β Pic, is addressed in Section 4.

Details of the emission lines observed and the profiles they exhibit are given in Table 3. Table 4 details the velocities of the components highlighted in Fig. 3. A description of each individual star follows, highlighting the most interesting features they show.

3.1.1 *HD 35187 (SAO 77144)*

This A2/3 IV/Ve star has previously been observed by Zuckerman (1994), Grady et al. (1996) and Böhm & Catala (1995), who all discuss the Hα line profile. HD 35187 is a binary star and it is likely that the spectra of all the above-mentioned work are a combination of the two stars, and not of HD 35187 alone. Our spectrum is also a combination of the two stars. The Hα profile we observe is clearly different from the observations reported by the first two of these papers. Although still a double-peaked structure, as found in these observations, the depth of the central absorption is less pronounced [Fig. 3(a)i]. The Hα observations of Zuckerman (1994) and Grady et al. (1996) both showed the absorption dipping below the surrounding continuum level, whilst our observations show the absorption minimum to be only just below the highest emission points. Our OAN resolving power of 15 000 is lower than that of Grady et al. ($R = 26\,000$) and Zuckerman ($R \simeq 40\,000$), but the difference between their Hα profiles and ours is too large to be caused by differences in resolving power alone. Böhm & Catala (1995) also observed the Hα profile of this star, at a resolution higher than that of Grady et al. or Zuckerman, and stated it to be single-peaked.

Table 5. Equivalent widths of the Hα, He I and Na D lines (excluding the interstellar lines present) shown in Fig. 3. Errors are a maximum of 0.05 Å for He I and Na D, 0.15 Å for Hα.

Star HD	SAO	Spectral Type	Equivalent Width (Å) Hα	He I	Na D_1	Na D_2
35187	77144	A2/3 IV/Ve	−4.74	0.23	0.19	0.22
139614	226057	A7Ve	−6.69	−0.19	0.25	0.29
141569	140789	A0Ve	−5.51	–	0.15	0.16
142666	183956	A8Ve	−3.23	0.11	0.27	0.29
144432	184124	A9/F0Ve	−9.00	−0.10	0.19	0.27
					−0.02	−0.06
158643	185470	B9.5Ve	−2.84	0.09	0.15	0.19
169142	186777	A5Ve	−13.97	−0.28	0.21	0.24

The He I λ5876 line is also variable. In our spectrum [Fig. 3(a)ii] a substantial absorption profile can be seen. However, both Grady et al. (1996) and Böhm & Catala (1995) found no evidence for either absorption or emission in their higher resolution spectra. This star has previously been studied as a HAeBe star (Grady et al. 1996; Böhm & Catala 1995) so variability in some lines should not be surprising. If it truly belongs in the category of HAeBe stars, rather than to the field Vega-like stars, our study highlights the similarities between the two classes, since inspection of the emission-line profiles presented here does not reveal any striking differences between this star and the rest of our sample of field Vega-like stars. The Na I D lines show a normal photospheric absorption profile.

3.1.2 HD 139614 (SAO 226057)

This A7Ve star (Fig. 3) is one of two stars that show single-peaked emission in their Hα line, the other being HD 169142 [Fig. 3(g)i and Section 3.1.7]. These two stars have the lowest values of v sin$i$ amongst the A-type stars in our sample (24 and 55 km s^{-1} respectively), indicating that we may be observing the stars and their discs pole-on. We find a weak core emission in the Na I D lines, centred on the heliocentric velocity of the star [Fig. 3(b)iii]. The He I line shows evidence of double-peaked emission [Fig. 3(b)ii], highly unusual for a star of this spectral type. A normal absorption profile is exhibited by the Ca II λ8498 triplet line.

3.1.3 HD 141569 (SAO 140789)

This A0Ve star shows a double-peaked Hα line, with the absorption almost centred on the heliocentric velocity of the star [Fig. 3(c)i]. The Hα line of this star has previously been studied for variability by Andrillat, Jaschek & Jaschek (1990) who considered it to be a 'quiescent' HAeBe object. They found a velocity separation of the two peaks of 274 km s^{-1}, which is close to our value of 242 km s^{-1} (Table 4). The broad, stellar sodium lines of this star [Fig. 3(c)iii] appear, at first glance, to be normal, but comparison with the LTE model for this star from Paper I using the v sin$i$ determined from other lines (Table 1) shows that the photospheric lines should be far broader and less deep than those observed. We suggest that this is due to the presence of additional circumstellar absorption. The central absorption velocity of the stellar line is highly blueshifted with respect to the star, implying an outflow of material. The blue wings of the D_2 line extend up to −300 to −400 km s^{-1}. The two doublet lines do not, however, have the same central velocity, with the D_2 line having a central absorption velocity over 100 km s^{-1} more negative than the D_1 line. This difference is too large to be attributable to calibration errors. The broad D_1 and D_2 equivalent widths (Table 5) are identical within the errors, which is also unexpected. The double-peaked Hα profile of HD 141569 most closely resembles that shown by HD 158643 [51 Oph, Fig. 3(f)i] and it is noteworthy that these two stars exhibit the highest values of v sin$i$ in our sample, 236 and 267 km s^{-1} respectively (Table 1). It seems likely that in both cases

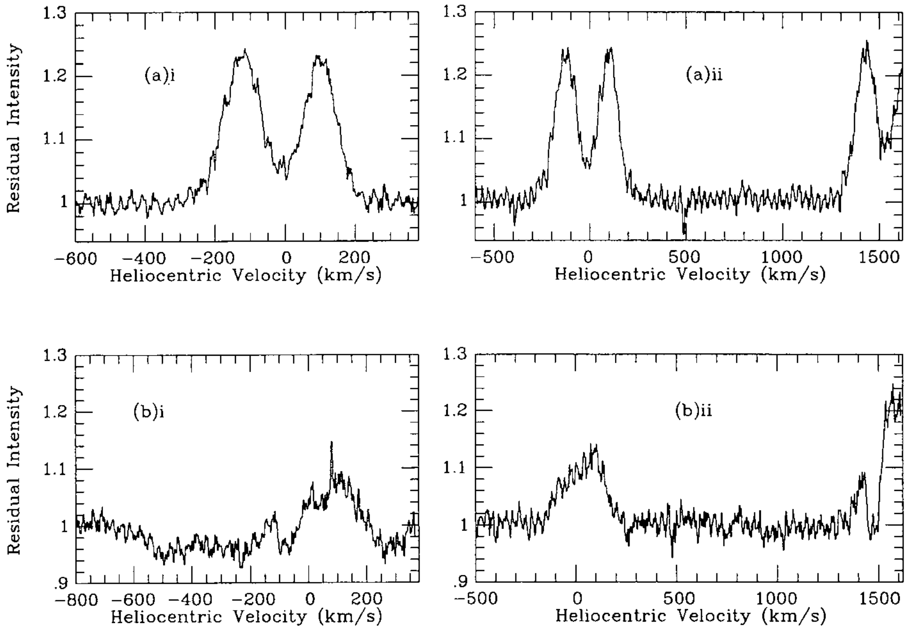

Figure 4. Components of the Ca II IR triplet in (a) HD 158643 (51 Oph, B9.5Ve) and (b) HD 144432 (A9/F0Ve). (i) 8662 Å, (ii) 8498 Å (λ8542 Å is only partially visible in the order). The ±2 per cent, high spatial frequency component is due to fringing which, during 1994, afflicted the spectrograph around the region of the Ca IR triplet. Velocities have not been corrected for the radial velocity of the star.

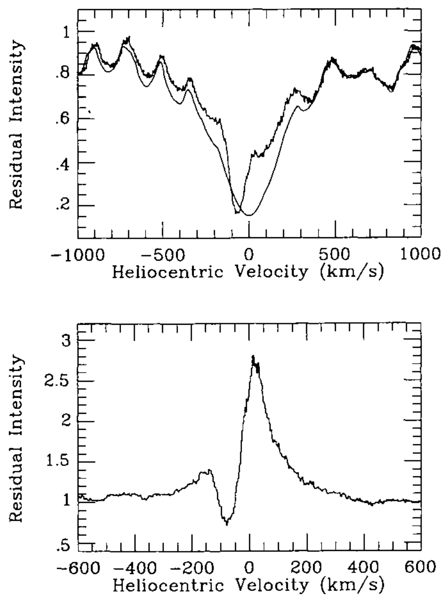

Figure 5. The Ca II K profile of HD 144432. The top frame shows the observed profile and the computed model (smooth line). The model was divided into the observed profile revealing the P Cyg structure in the lower frame.

the circumstellar lines originate from a rotating disc seen close to edge-on. Nothing unusual is seen in the Ca IR triplet lines.

3.1.4 HD 142666 (SAO 183956)

This A8Ve star was classed as a probable HAeBe star by Gregorio-Hetem et al. (1992), but is not associated with any obscured region or nebulosity. Our spectra show a double-peaked Hα profile [Fig. 3(d)i], with a highly blueshifted absorption, suggesting outflow of material. The Na I D line shows no abnormalities, and neither does the calcium triplet. There appears to be activity in the region of formation of the He I line with a possible inverse P Cyg profile present, despite the fact that He I is not expected to be present at the effective temperature of this A8-type star. No other line in the close proximity of the He I line is expected to be as strong as the profile that is seen.

3.1.5 HD 144432 (SAO 184124)

This (A9/F0)Ve star shows probably the most interesting profiles of the sample. A P Cyg profile is seen in the Hα line [Fig. 3(e)i], with the highest blueshifted absorption velocity amongst the stars studied here. A P Cyg profile is also observed in the Na I D lines, but with a more complex structure. Close examination of the D_1 line shows the possibility of an additional absorption, redshifted with respect to the emission, at positive velocities relative to the star [Fig. 3(e)iii]. This absorption can also be seen, more weakly, in the D_2 line. Such a profile is unexpected, but could perhaps be explained by the presence of both a disc and an envelope in the circumstellar environment. It is conceivable that the blueshifted absorption is due to an expanding envelope, inside which resides a disc of material, accreting matter on to the star. The idea of a disc and envelope coexisting is not new. Such a scenario has been put forward to explain the IR excesses observed for the Group II class of HAeBe stars (Hillenbrand et al. 1992).

A P Cyg profile is also seen in the Ca II triplet lines (Fig. 4b). The equivalent widths for the two wholly visible lines are $\lambda 8498 = 84 \pm 17$ mÅ and $\lambda 8662 = 83 \pm 17$ mÅ. The Ca II K line also showed evidence of a P Cyg profile (Fig. 5), although not as clearly. The class of profile for the K line was determined by dividing the model for this star from Paper I into the observed spectrum, revealing the P Cyg profile in the lower part of Fig. 5. Evidence of activity is also present in the He I $\lambda 5876$ line [Fig. 3(e)ii], which shows a double-peaked emission profile.

3.1.6 HD 158643 (SAO 185470, HR 6519, 51 Oph)

This has another interesting spectrum and is the only star in our sample that has previously been classified as a shell star (e.g. LH90). 51 Oph exhibits a pronounced near-IR excess due to hot dust, but lacks the far-IR excess, due to cool dust, that is typical of the other stars in our sample. It has the earliest spectral type in our study, B9.5Ve. Double-peaked emission, showing the characteristic pointed absorption associated with shell stars, has been found in both the Hα and the Hβ lines, with a centred absorption velocity [Fig. 3(f)i]. As noted above for HD 141569, the double-peaked Hα profile and high v sin$i$ for 51 Oph can be interpreted as indicating that the emission originates from a disc seen nearly edge-on. Like HD 141569, the broad stellar Na I D lines are far too narrow and deep for a star of its class and rotational velocity [Fig. 3(f)iii]. Again, we attribute this to the presence of additional absorption. Unlike HD 141569, there is evidence that the He I $\lambda 5876$ line is in absorption [Fig. 3(f)ii], but shifted to negative velocities. The calcium triplet lines, unlike HD 141569, do show evidence of emission, however, in the form of a double-peaked structure (Fig. 4a). Their equivalent widths are $\lambda 8498 = 151 \pm 20$ mÅ and $\lambda 8662 = 157 \pm 20$ mÅ. Narrow circumstellar lines have been found in the Ca II K line of 51 Oph. These are discussed more fully in Section 4.7.

3.1.7 HD 169142 (SAO 186777)

Like HD 139614, this A5Ve star shows single-peaked emission in Hα [Fig. 3(g)i] and also core emission in the Na D lines [Fig. 3(g)iii]. Again, like HD 139614, the helium $\lambda 5876$ line is in emission [Fig. 3(g)ii]. No unusual profiles are seen in the calcium lines.

3.1.8 HD 161868 (γ Oph) and HD 216956 (α PsA)

These two stars show no evidence of emission or other indications of activity in their spectra. As mentioned previously, both stars are MK standards (A0V and A3V respectively) and presumably represent a more evolved type of Vega-like star.

3.1.9 Discussion

Amongst the earlier type Vega-like stars, the two stars with single-peaked Hα emission (HD 139614 and 169142) show similar profiles in their sodium, helium and calcium lines. It should also be noted that these two stars both showed photospheric underabundances of more than 0.5 dex in silicon (Paper I). As noted earlier, FM84 stated that no HAeBe star with single- or double-peaked Hα emission showed emission in Na I D. By contrast, we find core Na I D emission in both of the Vega-like stars in our sample that show a single-peaked Hα profile. This might well be a result of our better resolving power. The consequences of variablility must also be taken into account. It is already well known that some HAeBe stars can show dramatic changes in their line profiles, which may affect comparisions of spectroscopic properties. Thus far, we have found that the only star in our sample that definitely shows variability in its Hα profile (HD 35187) has been classified as belonging to the HAeBe class (Böhm & Catala 1995; Grady et al. 1996). Three other stars of our sample (HD 141569, 142666 and 144432) have been suggested to be either an HAeBe star or candidate members of the class (table 1 of Thé, de Winter & Perez 1994), but do not satisfy all of the classical criteria of Herbig (1960) for membership of the class.

We found that both of the single-peaked Hα profile stars (HD 139614 and 169142) and the P Cyg Hα profile star (HD 144432) showed emission in the He I λ5876 line, whilst three double-peaked Hα stars (HD 35187, 142666 and 158643) showed excess He I λ5876 absorption. No significant He I absorption or emission is predicted to be present in the photospheric spectra of these A-type stars (see e.g. fig. 1 of Böhm & Catala 1995). We interpret the presence of excess absorption and emission in the He I λ5876 line as a signature of ongoing accretion in these systems, whereby impacting material leads to sufficiently elevated temperatures that net emission and absorption in the He I line can result. Böhm & Catala interpreted the excess He I line fluxes in their sample of classical Herbig Ae/Be stars as originating at the base of an expanding chromosphere, as their profiles were consistent with the rotational velocity of the relevant star. Another suggestion is that the excess He I fluxes come from a boundary layer between the star and a (non-magnetic) accretion disc. Hartmann, Hewett & Calvet (1994) have proposed magnetospheric accretion models for T Tauri stars, in which material is funnelled along field lines from the inner parts of a disc to elevated latitudes in both northern and southern hemispheres of the star. One prediction of their models is that double-peaked Balmer-line emission profiles should correspond to a system observed much closer to pole-on than to edge-on, while single-peaked profiles would correspond to a system observed closer to edge-on. However, as noted above, HD 139614 and 169142, the two stars with the lowest values of $v\sin i$ in our sample of A-type systems (and which are thus the most likely to be viewed pole-on), both exhibit single-peaked Hα profiles. Thus, while the presence of λ5876 absorption and/or emission is likely to be diagnosing phenomena occurring in the innermost regions of the star–disc system, exact parameters remain to be derived.

α PsA and γ Oph are A-type dwarf MK standards. They both have relatively low values of $L_{\rm IR}/L_*$ (Table 1) and lack any emission lines or signs of circumstellar activity. They may both be relatively old main-sequence stars.

51 Oph is a shell star with hot circumstellar dust and so does not fit easily into standard scenarios connecting main-sequence stars with cool dust discs to pre-main-sequence objects that also have cool dust in addition to warmer material. The remainder of the A-type stars in our sample exhibit high activity levels and large values of $L_{\rm IR}/L_*$. Although the profile correlations found for the Vega-like stars are different in detail from those found previously for HAeBe stars, the range of shapes and properties of the emission lines are similar. The spectroscopic similarity between these two classes of star suggests that they share common features in their circumstellar environment. Despite their spectroscopic similarities to HAeBe stars, particularly in their emission-line characteristics, the field A-type Vega-like stars in our sample are associated neither with obscured regions nor with reflection nebulae, and so they cannot be classified as classical HAeBe stars. Nor are these Vega-like stars associated with clusters, indicating typical ages somewhat higher than those of classical HAeBe stars and their analogues found in clusters. Classical HAeBe stars are believed to be pre-main-sequence, whereas our surface gravity analysis in Paper I indicated main-sequence parameters for the current sample of Vega-like stars. Given that the time-scale to reach the main sequence is less than 10^7 yr for stars with masses $M > 2\,{\rm M}_\odot$ and less than 3×10^6 yr for $M > 3\,{\rm M}_\odot$ (Palla & Stahler 1993), one would expect the field A stars in our Vega-like sample, which are distant from star-forming regions, to have already reached the main sequence. However, the high levels of emission-line activity that they exhibit and their large values of $L_{\rm IR}/L_*$ (Table 1) must indicate that they are still quite young, still possessing significant remnant discs from their formation epoch.

3.2 The later type stars – F4 to K5

We have found in the previous section that Herbig Ae/Be stars and the B9–A9 Vega-like stars in our sample show similar spectroscopic signatures. This raises the obvious question of whether the later type Vega-like stars have similar properties to the low-mass counterparts to Herbig Ae/Be stars, namely the T Tauri stars. In the 1940s, Joy found a number of stars with late spectral type exhibiting 'emission lines resembling the solar chromosphere'. These objects also showed light variations and were associated with nebulae (Joy 1945). He named this class of star after the brightest member, T Tauri. Their pre-main-sequence nature is now undisputed after having been confirmed by several methods (Herbig 1962, 1977; Jones & Herbig 1979; Cohen & Kuhi 1979) and a large amount of work has been carried out on these young stars since then (see Bertout 1989 and Hartmann 1990 for reviews of work on T Tauri stars).

Classical T Tauri stars were originally defined by the criteria of Herbig (1962), who noted that (a) hydrogen Balmer lines and Ca II H and K lines are in emission; (b) anomalous emission in Fe I $\lambda\lambda$4063, 4132 is often observed; (c) forbidden emission lines of [O I] and [S II] are observed in many stars of this type; and (d) the Li I λ6708 absorption line is very strong. Due to the variablility of T Tauri stars, Bastien et al. (1983) suggested that these criteria may not be fulfilled by the stars all of the time, and suggested the following for membership of this class: that they lie in an obscured region, have Hα, Ca II H and K emission, and a spectral type later than F. Following these criteria, T Tauri stars are seen to have broad and bright emission lines, excess IR emission and diluted photospheric absorption lines. Evidence for outflow has been found in some T Tauri stars from the presence of P Cyg profiles in the spectra (e.g. Hamann & Persson 1992). On occasion, both blue- and redshifted absorption profiles appear in the same object, implying that both infall and outflow are occuring simultaneously. Obviously this suggests that T Tauri stars have a very active and complicated circumstellar environment.

The source of energy driving the emission lines seen in T Tauri stars has been debated for some time. Herbig (1970) first proposed the 'solar chromosphere model', suggesting that the activity was similar to that seen in the solar transition region, and in the flares also seen from the Sun. However, later work (Calvet & Alberran 1984) showed that this model failed to reproduce the necessary energy requirements by one or two orders of magnitude for the most extreme classical T Tauri stars, although they could account for the 'naked', or weak, T Tauri stars sometimes observed. Advances in instrumentation and detectors showed that the discrepancy between the energy produced by the solar chromosphere model and that required to fit the observations was larger than previously thought,

Table 6. Details of line characteristics for the later type stars in our sample. Heliocentric velocities ($V_{\rm emis}$, in km s^{-1}) are listed for the emission peaks, and equivalent widths (EW, in Å) for the complete stellar line.

Star		Spect.		Hα		Na D$_1$		Na D$_2$		Ca K		Ca Triplet	
HD	SAO	Type	V$_\odot$	$V_{\rm emis}$	EW	$V_{\rm emis}$	EW	$V_{\rm emis}$	EW	$V_{\rm emis}$	EW	$V_{\rm emis}$	EW
23362	111388	K2V	-	—	1.13	—	1.42	—	1.87	—	—	—	—
98800	179815	K5Ve	12.5±0.4	−1.94	0.19	—	6.65*	—	6.65*	+11.1	10.5	+14.9	0.74
123160	158350	G5V	−6.4±0.4	—	3.34	—	0.53	—	0.64	+5.3	12.98	—	0.94
135344	206462	F4Ve	−3±3	−10.45	−14.41	+7.3	0.28	+5.6	0.33	—	9.39	—	1.09
143006	143006	G5Ve	−0.9±0.3	−31.0	−8.35	—	0.76	—	0.81	+3.4	12.1	−0.1	0.73

*The equivalent width is for the D$_1$ and D$_2$ lines combined.

which called for a new model to be considered. The major reason for the downfall of the solar chromosphere model was its inability to reproduce the excess IR emission associated with these stars. The accretion disc model is now the most widely accepted as being the driving source of activity, whilst simultaneously explaining the observed IR excesses. In this model, the IR excess arises from the disc, while the optical–UV emission also seen from these stars would come from a hot boundary layer where disc material accretes on to the surface of the star. Some of the 'chromospheric' lines such as Hα are expected to arise from envelopes moving away from the star (see Hartmann 1990 for further discussion of this topic).

T Tauri emission lines can exhibit narrow and broad components at the same time, whilst some exhibit evidence for simultaneous infall and outflow. Hamann & Persson (1992) carried out a study of 53 T Tauri stars to characterize the near-IR spectra of these stars. They studied the emission from many lines in the 6450–9210 Å region, as well as obtaining 'blue' spectra to cover other important lines such as Ca II H and Na I D lines. Other optical spectroscopic work on T Tauri stars can be found in, for example, Franchini et al. (1992).

Here we study the emission lines seen in the spectra of our late-type sample of Vega-like stars, and compare them to those observed by others. Table 6 lists properties of the lines in which emission was found, and the type of profile exhibited. The spectra of the stars are shown in Figs 6 and 7. After a description of the individual stars and their most interesting features, we summarize the results and draw comparisons where possible with younger, pre-main-sequence stars.

3.2.1 *HD 23362 (SAO 111388)*

The spectral coverage for this K2V star did not extend to the Ca II H and K resonance lines, but data for the Na I D region (Fig. 6b) and longer wavelengths are available. There is no evidence for emission in the Hα (Fig. 6a) or calcium triplet lines. In fact, no signs of activity are found in the spectrum of this star. In Section 2 we questioned the youth of this star, and again suggest that HD 23362 is not a young object.

3.2.2 *HD 98800 (SAO 179815)*

This is a K5V star that has been extensively studied recently (see Section 2 for more details). It shows clear signs of activity. Emission is prominent in the Ca II K and H lines (Fig. 7a), showing a single peak with central velocity only a few km s^{-1} redward of the heliocentric velocity of the star. Emission is also visible in the core of the calcium triplet, with the peak not quite reaching the continuum level (Fig. 7b). A filling-in of the Hα line is present (Fig. 6c), as noted by Fekel & Bopp (1993). The apparent very weak infilling in the cores of the Na D photospheric absorption lines (Fig. 7d) can instead be attributed to the blending of the lines arising from components Aa and Ba. In Section 2 we presented evidence that HD 98800 is probably very young. The youth and activity of this star could indicate that it has a T Tauri nature. Gregorio-Hetem et al. (1992) completed a photometric and spectroscopic study of HD 98800 and classified it as a 'weak-lined' T Tauri star. The lack of net Hα emission and the fact that it is not located in an obscured region disqualify it from being considered as a classical T Tauri star according to the criterion of Bastien et al. (1983). Fekel & Bopp (1993) noted that its spectrum was very similar to the BY Dra class of stars, a type of flare star showing small regular variations in brightness. Most BY Dra stars are found in binary systems.

3.2.3 *HD 123160 (SAO 158350)*

This G5V star shows 'normal' Hα (Fig. 6e) and Na I D lines (Fig. 6f), and only weak Ca II K and H emission in the cores of those lines (Fig. 7c). The calcium triplet lines appear normal (Fig. 7d) and there are no other apparent signs of activity. From the presence of chromospheric activity and a relatively strong lithium line (Section 2) this star appears to be a young object, but apparently has a more quiescent circumstellar environment than those found around younger, T Tauri class stars.

3.2.4 *HD 135344 (SAO 206462)*

This is the hottest of the stars in our later type sample (F4Ve), and shows single-peaked emission in the Hα (Fig. 6g) and Hβ lines, with the peaks slightly blueshifted with respect to the velocity of the star. The Na I D lines, which exhibit core emission (Fig. 6h), provide the only other sign of activity in this star, although there may be some infilling of the Ca II λ8498 absorption line (Fig. 7f).

3.2.5 *HD 143006 (SAO 183986)*

This G5Ve star may be the youngest star in our sample (see Section 2). Previously catalogued as an emission-line star (Herbig & Bell 1988), it shows strong Hα emission in the form of a slightly blueshifted single peak (Fig. 6i). This single-peaked structure is also visible in the Ca II K and H lines (Fig. 7g), more or less centred on the heliocentric velocity of the star. Core emission is also seen in the calcium triplet lines (Fig. 7h).

HD 143006 also had narrow emission 'spikes' in its spectrum. Whilst reducing the original data it was noted that narrow spikes that one might normally associate with cosmic rays were repeated on successive exposures. Subsequent analysis of these lines showed

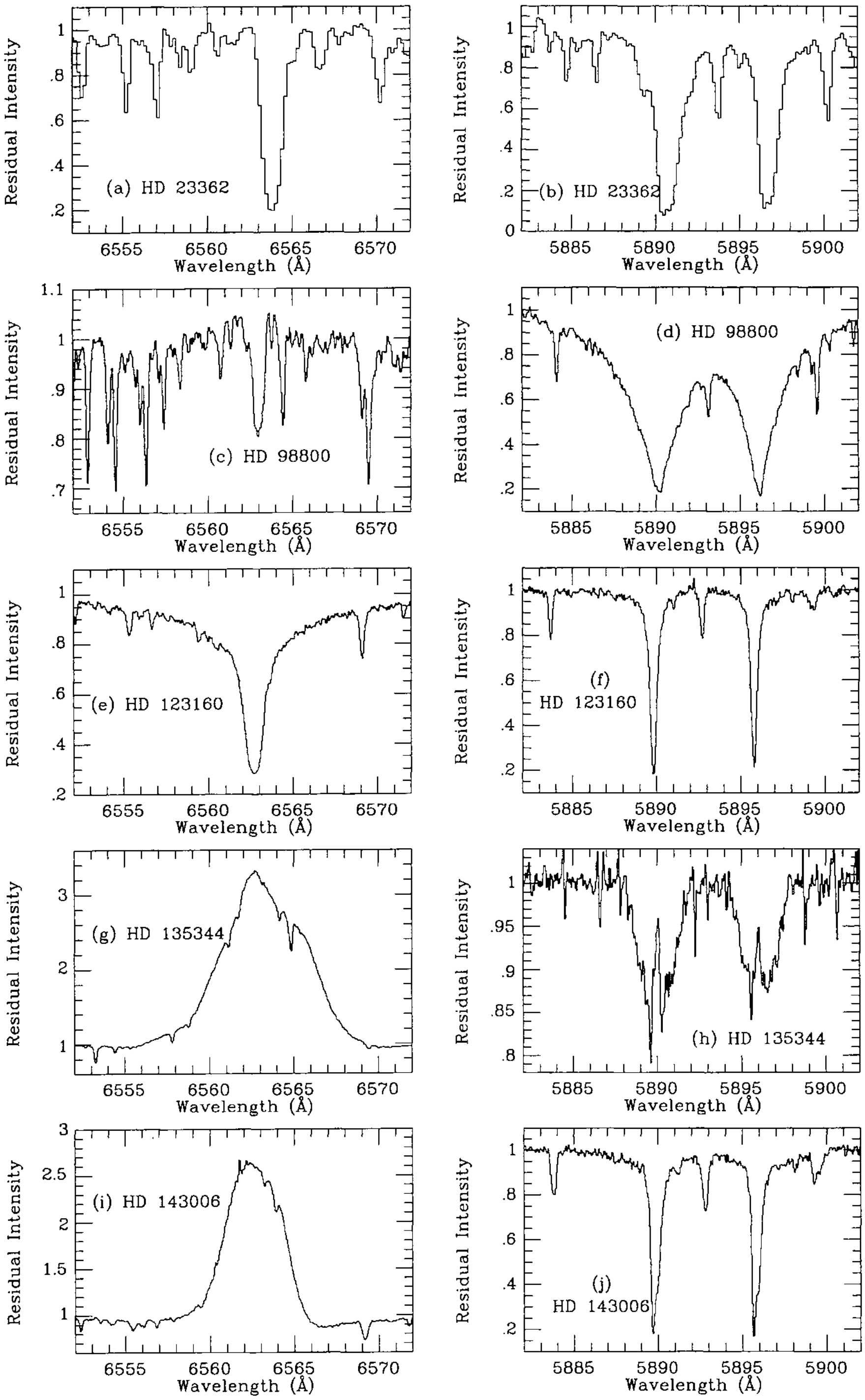

Figure 6. The Hα (left column) and Na D (right column) region of the five later type stars in our sample: (a) and (b) HD 23362 (K2); (c) and (d) HD 98800 (K5Ve); (e) and (f) HD 123160 (G5V); (g) and (h) HD 135344 (F4Ve); (i) and (j) HD 143006 (G5Ve).

them to have FWHM values consistent with the resolution of the spectrum, and they are believed to be real. Table 7 lists the rest wavelengths of the narrow emission lines (corrected for the radial velocity of the star), their FWHM and equivalent widths.

3.2.6 Discussion

In the small sample of five later type (F4–K5) Vega-like stars that we have observed, we have found one star (HD 23362, K2V) that shows no sign of activity nor of surface lithium and which thus appears to be an older object than the remainder of our sample. The rest of the objects show indications of activity at varying levels. HD 123160 shows only weak emission in its Ca II K line, but none in the lines of Hα or Na I D. It was also found to have the lowest surface lithium abundance other than HD 23362, and may therefore be older than the three more active late-type stars in our sample (HD 98800, 135344 and 143006). The hottest of the late-type stars (HD 135344, F4Ve) shows emission in its Hα (Fig. 6g) and Hβ

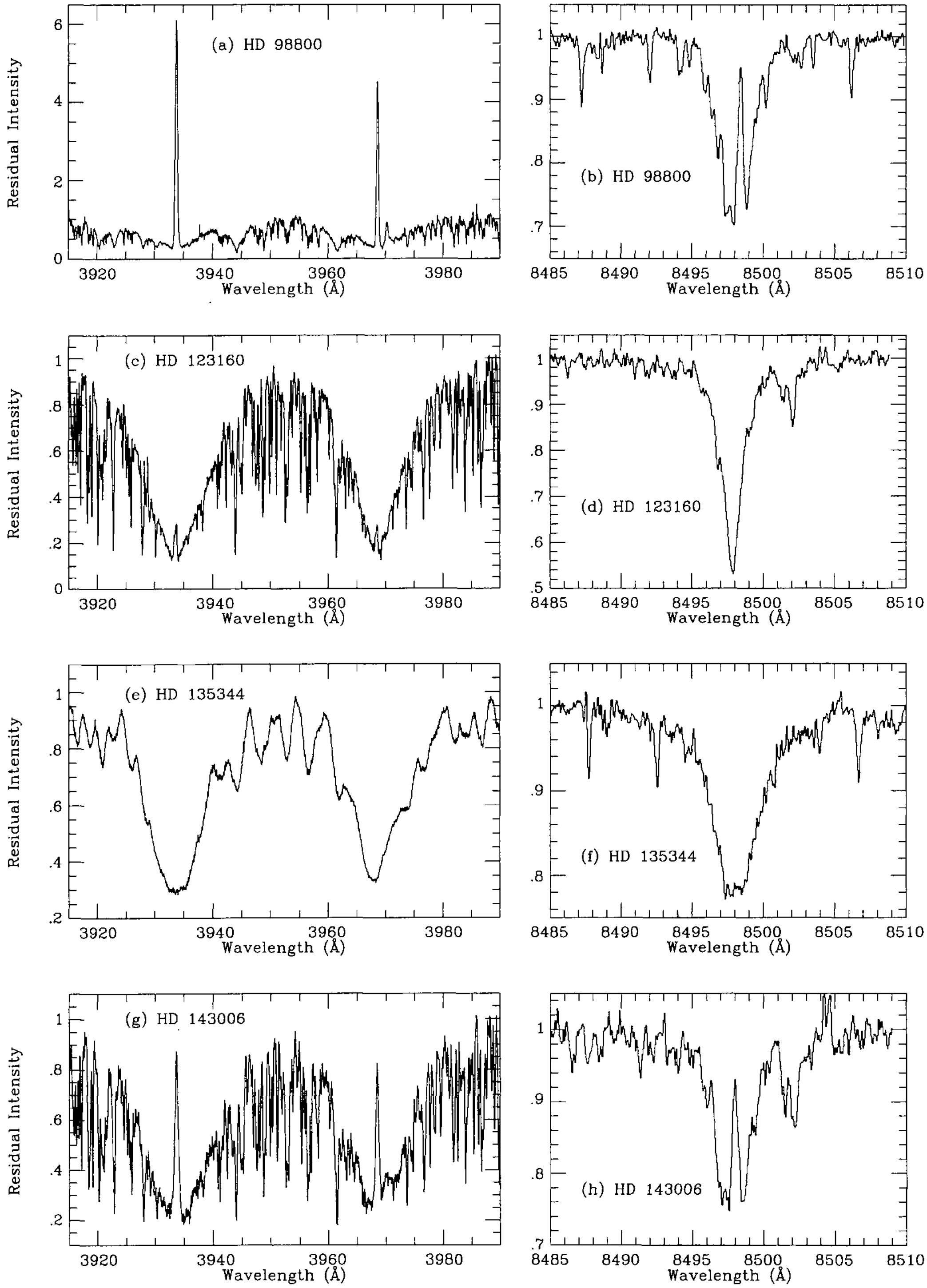

Figure 7. Ca II line profiles for the later type stars of our sample. Left column: the Ca II H & K lines; right column: the Ca II triplet line at 8498 Å. (a) and (b) HD 98800 (K5Ve); (c) and (d) HD 123160 (G5V); (e) and (f) HD 135344 (F4Ve); (g) and (h) HD 143006 (G5Ve).

lines, and also core emission in the Na I D lines (Fig. 6h). HD 143006 is also active, showing emission in its Hα line (Fig. 6i) and in its Ca II K, H and triplet lines (Figs 7g and h). It also has an extremely high Li abundance (Table 2), implying that it is the youngest star in our late-type sample. Its fractional IR luminosity, $L_{IR}/L_* = 0.56$, is one of the highest in our sample, putting it within the range of those found for T Tauri stars (e.g. see Sylvester et al. 1996, table 17). HD 98800 also has a high fractional IR luminosity (0.084), and shows clear signs of activity through emission in its Ca II K, H and triplet lines, and filled-in emission in its Hα line. Once again, this star has a high surface lithium abundance, implying that it is very young.

Table 7. Narrow emission lines found in the spectrum of HD 143006.

λ_{rest}	FWHM (Å)	EW(− mÅ)
5577.11	0.13±0.01	46±1
7315.98	0.17±0.02	18±1
7793.80	0.24±0.02	30±2
7992.94	0.29±0.03	32±2
8344.25	0.22±0.01	72±2
8398.83	0.22±0.01	61±5
8464.88	0.16±0.02	16±2
8465.27	0.24±0.03	22±2
8504.67	0.15±0.02	13±2
8505.08	0.20±0.03	13±3
8760.95	0.19±0.02	19±3
8761.25	0.20±0.06	12±3
8767.92	0.21±0.02	30±2
8885.47	0.27±0.01	87±2
8902.77	0.24±0.02	33±2
8919.32	0.34±0.02	76±3

None of the late-type stars in our sample shows P Cyg profiles, which would be indicative of outflowing material.

4 NARROW INTERSTELLAR AND CIRCUMSTELLAR ABSORPTION COMPONENTS

The presence of IR excesses due to dust emission around our programme stars implies that some unknown quantity of gas should also be present in their circumstellar environments. The Vega-like prototype, β Pic, first had its dust-disc imaged by Smith & Terrile (1984). A gaseous absorption counterpart to this edge-on disc was discovered at visible wavelengths by Hobbs et al. (1985) and at ultraviolet wavelengths by Kondo & Bruhweiler (1985). Since then, many studies have been carried out for similar stars suspected of having circumstellar material, namely IR-excess stars and shell stars (e.g. Hobbs 1986; LH90 Holweger & Rentzsch-Holm 1995). In general, very few positive detections of gaseous absorption components around these stars have been made. LH90 studied 49 stars in a search for β Pic-like objects, and found only six stars that had evidence for circumstellar gas. Holweger & Rentzsch-Holm (1995) found that a higher percentage (30 per cent) of their sample of shell stars and λ Boo stars had circumstellar absorption components, but they did state that their sample was incomplete and biased towards objects well known to have circumstellar material, such as β Pic and 51 Oph. Overall, a lack of detected gas absorption in the circumstellar environment is apparent. In an effort to expand the sample of IR-excess stars studied for the presence of circumstellar gas absorption, we have analysed the Ca II K and Na I D lines of our programme stars, and present our findings below.

Narrow absorption lines in one or both of the Ca K or Na D regions were found for seven of the 14 stars analysed (the wavelength coverage of our spectra of HD 23362 and 35187 did not extend to the Ca II K line). The properties of the observed components are listed in Table 8, with upper limits corresponding to a non-detection of a narrow absorption component. IS/CS gives our interpretation of the origin of the narrow absorption components, either interstellar (IS) or circumstellar (CS).

With just a single observation, it can be virtually impossible to distinguish a circumstellar line from an interstellar one. Definitive identifications can be made with the help of multiple observations of the same line – variations of the line would indicate a circumstellar origin. The simultaneous detection of narrow absorption components at the same velocities from excited-state lines would also indicate the presence of circumstellar material, as would the presence of absorption components at highly shifted velocities. β Pic has a strong, saturated stable circumstellar Ca K component centred on the radial velocity of the star (e.g. Crawford et al. 1994). This stable line is considered to be the result of absorption due to its disc – because it is edge-on, there should be no offset to the radial velocity of this component. Should other discs also be observed edge-on, similar components centred on the stellar heliocentric velocity should be observed. The presence of some or all of the above indicators would go some way to a positive identification of cool circumstellar gas and these criteria have been used in assessing the origin of some of these lines.

The lines of sight to many stars will also cross areas of space that are host to interstellar material. This material can be detected in the form of narrow absorption lines (superimposed on the broad stellar lines) which can be virtually indistinguishable from those of circumstellar origin. One way of checking the probability of lines being interstellar is to observe adjacent lines of sight to the target star in order to look for correlated velocity structure. This method can be extremely time-consuming. However, many interstellar clouds and regions have already been observed and mapped, e.g. by Dame et al. (1987) in CO. If the lines of sight pass close to, or through, a known interstellar region, then correspondence between

Table 8. Equivalent widths (in mÅ) and heliocentric velocities (in km s^{-1}) of the narrow absorption lines present in the spectra of the programme stars. Upper limits are given where absorption was not visible. For figures in brackets (HD 135344), see Section 4.2.

Star		Na I D_1		Na I D_2		Ca II K		IS/CS?
HD	SAO	EW	$V_\odot$	EW	$V_\odot$	EW	$V_\odot$	
35187	77144	79±3	21.8±0.3	125±5	21.7±0.4	Not available		IS
135344	206462	(33±10)	(−17.9±1.3)	(40±8)	(−18.4±2.5)	< 1.8	-	IS
141569	140789	102±3	−13.3±1.3	110±3	−13.5±2.5	11.4±0.9	−15.8±3.0	IS
142666	183956	233±4	−12.8±2.5	282±6	−14.2±2.5	23.2±2.4	−12.6±1.5	IS
144432	184124	19.1±2.1	−21.5±2.5	31.0±1.1	−21.6±1.3	< 2.2	-	IS?
		20.4±1.8	−10.0±1.3	41.1±1.2	−10.1±2.5	-	-	IS?
		0.9±0.2	−91±3	0.9±0.2	−95±3	4.9±2.1	−95±3	CS
158643	185470	13.2±1.0	−19.0±1.3	19.5±1.2	−20.4±1.3	21.7±0.6	−20.5±1.5	CS+IS
161868	122754	< 2.7	-	< 2.7	-	6.7±0.4	−31.2±1.5	IS

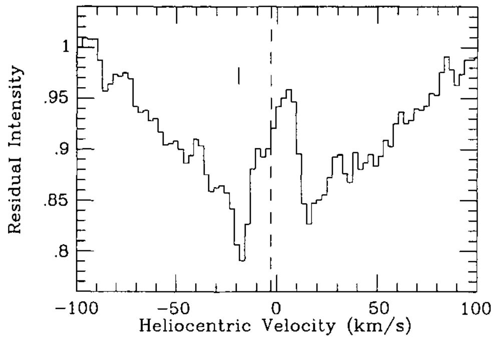

Figure 8. The Na I D_2 region of HD 135344. The dashed line corresponds to the radial velocity of the star. The tick mark indicates the possible narrow absorption component.

velocities can be looked for. For some stars, we have done this by comparing velocities calculated from the work of Dame et al. (1987) or from Lallement et al. (1995) for the Local Interstellar Cloud (LIC) and G clouds. An identification with interstellar material is made where there is evidence for a correlation between the predicted and observed velocities, or where there is no other evidence suggesting the presence of circumstellar material.

4.1 HD 35187 (SAO 77144)

The wavelength coverage of our spectrum of this star did not encompass the Ca II K line. The Na I D lines have previously been observed by Grady et al. (1996), who noted a single narrow absorption in the core of the stellar line. Our data confirm this observation and note no additional CS line. Previous reduction of these data produced a spurious line, in addition to the interstellar line shown in Fig. 3(a)iii, which we then believed to be of a circumstellar origin. Closer scrutiny and re-reduction of the data show this line to be an artefact. Hence the figure shown in Dunkin, Barlow & Ryan (1997b) is not correct. The velocity of the single line seen here [Fig. 3(a)iii] is 21.7 km s^{-1}, consistent with that of the Taurus dark cloud. Zuckerman (1994) also noted the association of HD 35187 with this region and we conclude that the line is of interstellar origin.

4.2 HD 135344 (SAO 206462)

Whilst no narrow Ca II K absorption components can be seen (Fig. 7e), the Na I D lines show emission within the core (Fig. 6h). Bluewards of this emission there is evidence of narrow absorption. This area of the spectrum was heavily contaminated by telluric water lines, and the residuals of the division by an atmospheric standard star can be seen either side of the stellar Na I D lines themselves (Fig. 6h). Careful inspection of the original raw spectra of HD 135344 and of an atmospheric standard star (HR 8425) indicates that the coincidence in velocities, -18 km s^{-1}, of the very narrow D_1 and D_2 absorption components cannot be attributed to coincident telluric absorption lines. The asymmetry of the central Na I D emission component and the narrowness of the -18 km s^{-1} absorption component (Fig. 8) lead us to interpret the latter as being due to a circumstellar or an interstellar absorption component. The velocity of the line does not correspond to that predicted for either the LIC or the G clouds in the local solar environment (Lallement et al. 1995), and the equivalent widths of the lines indicate that they are too strong to originate from these low-density clouds anyway. The star is 84 pc distant, so it is possible that the line of sight intersects an interstellar cloud beyond the LIC and G clouds. Since narrow circumstellar absorption components are usually stronger in the Ca II K line than in the Na I D lines, we assign an 'unknown, but probably interstellar' origin to the line.

4.3 HD 141569 (SAO 140789)

This star shows a clear narrow blueshifted absorption in the core of the stellar Ca II K line (Fig. 9a). There is a possible indication of an additional component in its blue wing, but this is difficult to confirm in the noise. Matched in velocity to the Ca II K is the absorption seen in Na I D (Fig. 9b). The D lines are very strong and prominent, and the ratio of the strength of the Na D lines to the Ca II K line is consistent with that observed in relatively dense interstellar clouds, where much of the Ca is interpreted as having accreted on to grain surfaces. Since the star is at a distance of over 200 pc, it seems very likely that the observed absorption line is of interstellar, rather than of circumstellar, origin.

4.4 HD 142666 (SAO 183956)

There is a narrow absorption component in the core of the Ca II K stellar profile (Fig. 9c), matched in velocity to a narrow absorption component seen in the Na I D lines (Fig. 9d). There is a slight asymmetry in the blue wing of the narrow Na I D absorption component, possibly indicating another unresolved component. Like HD 141569, the Na D lines are far stronger than that of Ca II K, suggesting that the lines originate from a relatively dense interstellar cloud.

4.5 HD 143006 (SAO 183986)

This star shows an asymmetry in its Ca II K core emission (Fig. 7g), interpreted as an absorption on the blue side of the emission peak. The Na I D absorption profile (Fig. 6j) also shows a sharp narrow absorption to the blue of the absorption core. Because of the uncertainty involved in trying to separate the stellar component of the Ca II K and Na I D lines from the non-stellar component, we have not attempted measurement of the velocity or the equivalent width of any narrow absorption component. However, since HD 143006 is 82 pc distant (Sylvester et al. 1996), it is likely that any narrow absorption present will be of interstellar origin.

4.6 HD 144432 (SAO 184124)

The Na I D lines of this star exhibit strong P Cyg profiles [Fig. 3(e)iii]. Within this profile are two narrow absorption lines (Fig. 10) whose velocities and equivalent widths are listed in Table 8. In addition to these components, the blueshifted absorption part of the P Cyg profile also shows the suggestion of a narrow component in its core. The corresponding heliocentric velocities are -91 ± 3 km s^{-1} for the D_1 line and -95 ± 3 km s^{-1} for the D_2 line. A very weak component at -95 ± 3 km s^{-1} is also visible in the Ca II K line (Fig. 5). The velocity of this narrow component is far too high to be of interstellar origin and we therefore conclude that it is caused by fast outflowing material in the circumstellar environment. The equivalent widths of the D_1 and D_2 lines are equal within the errors, which suggests that the line is saturated. This could be explained by the presence of clumpy material in the outflow whose covering factor of the background star in the line of sight is small. A similar

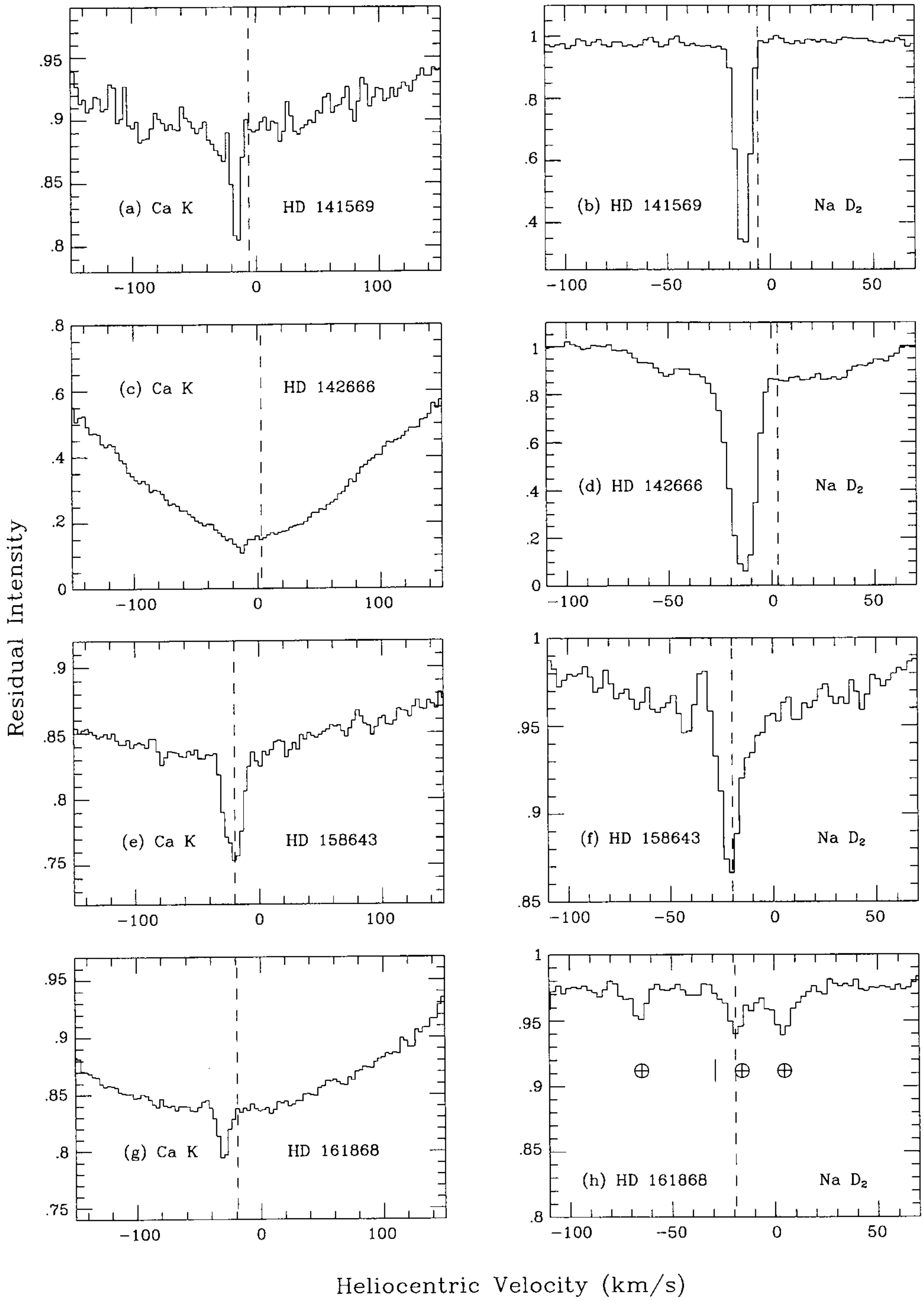

Figure 9. Close-ups of narrow absorption lines seen in the Ca II K and Na I D_2 lines. The vertical dashed line indicates the radial velocity of the star. The Na I D_2 region of HD 161868 is included for information only – the ⊕ symbols indicate telluric lines, while the tick mark shows the corresponding velocity of the component seen in Ca K.

effect has been modelled for β Pic by Lagrange-Henri et al. (1992), who have argued that in some cases the absorbing clouds are clumpy with respect to the stellar surface.

The origin of the other two narrow absorption components that lie at -21.5 and $-10.0\,\mathrm{km\ s^{-1}}$, between the absorption and emission peaks, is not so certain. Although we cannot discount the possibility that they originate in the near-stellar environment, especially because of the presence of P Cyg profiles indicating circumstellar outflow, an interstellar origin cannot be overlooked. Because the star is 119 pc distant (Sylvester et al. 1996), it is likely that at least one of these components is interstellar. The fact that these components are not visible in Ca II also supports an interstellar origin, since circumstellar components are usually seen more strongly in Ca II K than in the Na I D lines.

4.7 HD 158643 (SAO 185470, 51 Oph)

51 Oph is a very well-studied object. Our spectrum, obtained with

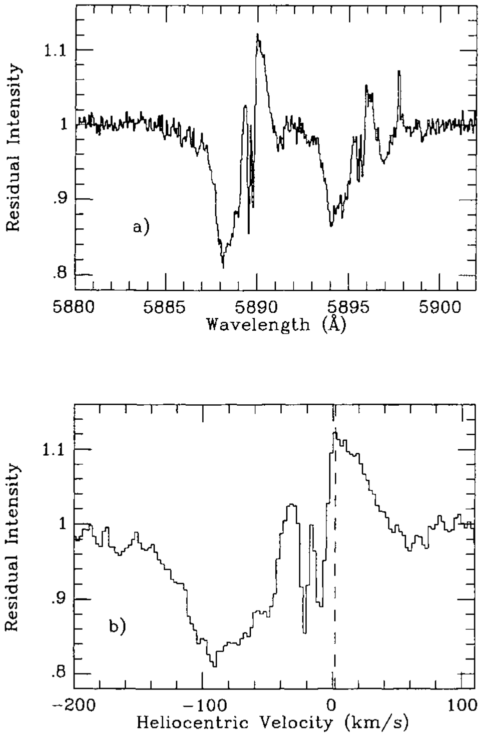

Figure 10. Na I D region of HD 144432. (a) shows the P Cyg profiles of both D lines whilst (b) shows the detail of the D_2 line. Both profiles have been normalized to unity, while the dashed line represents the radial velocity of the star.

a resolving power of 44 000, can resolve only one component in the Ca II K line, but asymmetries in the line suggest additional, unresolved components (Fig. 9e). LH90, using a resolving power of 100 000, resolved the line into three components, which were subsequently modelled by Bertin et al. (1993). More recently, the Ca II K line has been studied by Crawford, Craig & Welsh (1997) with ultrahigh resolution ($R = 860\,000$). They found that five components were required to fit their data accurately. Their spectrum is reproduced in Fig. 11(b) (Crawford, personal communication) along with the UCLES spectrum obtained during the current work (Fig. 11a). The full structure of the line is clearly resolved in the UHRF spectrum, revealing substructure hidden within the UCLES spectrum. Evidence for a circumstellar origin for some of these lines can be found in the detection of narrow absorption components in Fe II lines (Table 9 and Figs 11c and d) which correlate in velocity to each other, and to some of the components observed in the Ca II K line (Table 10). Since the Fe II lines are excited-state lines and are not found in the interstellar medium, we conclude that they are of circumstellar origin. The UCLES profiles of the Fe II λ4583 and Ca II K lines are plotted over the Ca II K UHRF data of Crawford et al. in Fig. 11(e). By inspection, it is clear that the Fe II line straddles the two most redward of the Ca II K components, implying a circumstellar origin for both of these components also. The properties of these components are listed in Table 10. The Fe II line also shows evidence of asymmetry in its blue wing. Since this asymmetry is present in all of the Fe II lines, we conclude that the feature is real and suggestive of additional components within the lines. Again, from inspection of Fig. 11(e), the material causing the central component in the Ca II K line appears to be contributing to the Fe II lines. From this we conclude that the central component in the UHRF spectrum of the Ca II K line is also circumstellar.

A narrow absorption component is visible in the Na I D lines of 51 Oph (Fig. 9f). This has been observed previously by LH90, whose data suggest three components, which cannot be seen in our lower resolution data. The velocities of the Na I D and Ca II K lines match within the errors (Table 10). Because of this, and the discussion above, we assign a circumstellar origin to at least some of the material causing the Na I absorption. Higher resolution UHRF observations are needed to reveal the full structure of the Na I D lines.

The blueward component in the Ca II K line in Crawford et al. (1997) data (Fig. 11) was best fitted by them with two lines. The

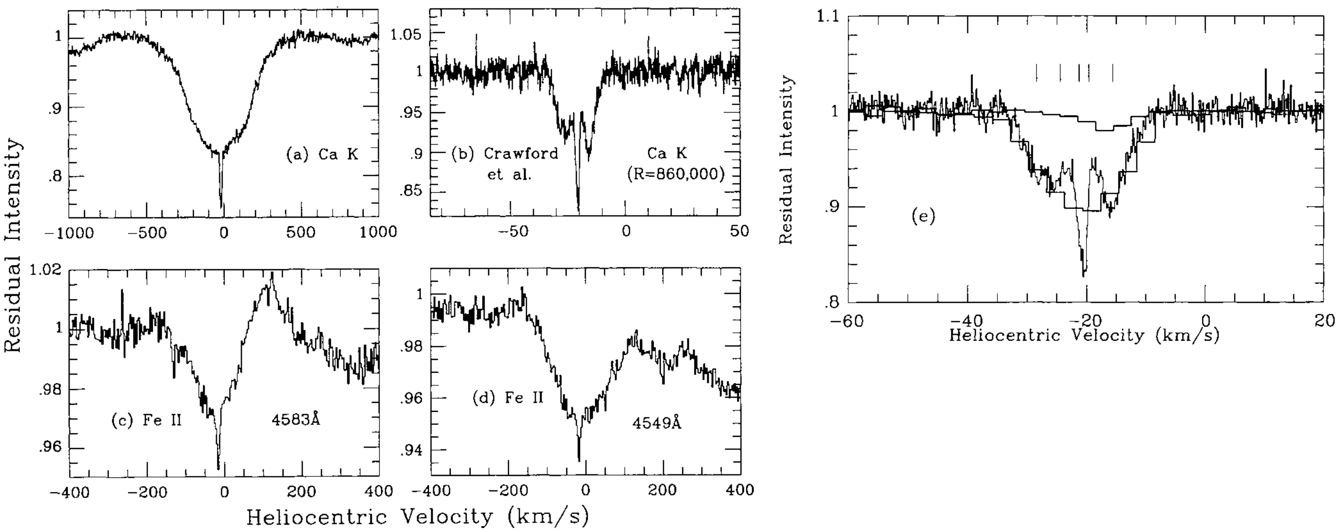

Figure 11. The UCLES spectrum of 51 Oph from the present work: (a) shows the broad stellar line, while (b) the UHRF spectrum of Crawford et al. (1997) shows the narrow Ca II K absorptions alone. Narrow components are also seen in the cores of the λλ4583 and 4549 excited-state lines of Fe II (c and d). Panel (e) shows an overlay of the ultrahigh-resolution Ca II K spectrum with the lower resolution UCLES spectra of the Ca II 3933-Å (lower) and Fe II 4583-Å lines. The tickmarks in (e) represent the velocities of the five components identified by Crawford et al. (1997).

Table 9. Fe II lines exhibiting a narrow absorption component in their profiles in the spectrum of 51 Oph.

Wavelength	Equivalent width (mÅ)	$V_\odot$ (km s^{-1})	Excitation potential (eV)	log *gf*	Ref.
4386.585	4.3±0.4	−18.51±1.25	2.583	−4.945	1
4549.474	2.2±0.3	−16.59±0.42	2.828	−1.957	2
4583.837	2.8±0.2	−17.00±0.50	2.807	−1.802	2
4923.927	5.7±0.6	−16.50±1.25	2.891	−1.559	2

1. Kurucz (1988).
2. Fuhr, Martin & Weise (1988).

Table 10. Heliocentric velocities (km s^{-1}) and total equivalent widths (mÅ) for the narrow interstellar/circumstellar components seen in 51 Oph. The Na I D measurements correspond to the D_2 line, while the Fe II line is at 4583 Å.

This work R = 44 000						Bertin et al. (1993) R = 100 000				Crawford et al. (1997) R = 860 000	
Ca II		Na I		Fe II		Ca II		Na I		Ca II	
$V_\odot$	EW	$V_\odot$	EW	$V_\odot$	EW	$V_\odot$	EW	$V_\odot$	EW	$V_\odot$	EW
										−29.18±0.14	
						−26.9±1.0		−26.9±1.0		−25.02±0.10	
−20.5±1.5	21.7±0.6	−20.4±1.3	19.5±1.2	−17.0±0.5	2.8±0.2	−21.3±1.0	20±3*	−21.3±1.0	18±5*	−21.22±0.05	20.32±0.55
						−16.0±1.0		−16.0±1.0		−20.29±0.03	
										−15.83±0.08	

Notes: *the equivalent widths were taken from LH90, the original source of the data analysed by Bertin et al. (1993).

velocities of these lines match extremely well with those expected for the LIC and G clouds in this direction. The strengths of the lines also support a local interstellar origin, and Crawford et al. (1997) do indeed identify these components as arising from the LIC (−25.0 km s^{-1}) and G (−29.2 km s^{-1}) interstellar clouds.

4.8 HD 161868 (SAO 122754, γ Oph)

A clear narrow absorption line near the centre of the core of the stellar Ca II K line is seen (Fig. 9g). This component was also observed and modelled by Bertin et al. (1993), with their velocity and equivalent width matching well those found here (Table 8). Crawford et al. (1997) have obtained ultrahigh-resolution observations of this line and find that it resolves into two components. Bertin et al. (1993) also found a corresponding line in their Na I D data, but it could not be seen in our spectrum due to contamination by telluric lines, even after division by an atmospheric standard stellar spectrum. Although the strengths of these lines are consistent with the LIC and G clouds, their velocities are not (Lallement et al. 1995). It is probable that other local interstellar material is causing the lines seen towards γ Oph.

4.9 Other stars

No narrow absorption components can be seen in either the Ca II K or Na I D line profiles of HD 23362 (SAO 111388), HD 98800 (SAO 179815), HD 123160 (SAO 158350), HD 139614 (SAO 226057), HD 169142 (SAO 186777) and HD 216956 (SAO 191524, α PsA).

5 CONCLUSIONS

We have analysed a sample of 14 stars classed as Vega-like or having an IR excess attributable to dust emission.

In our analysis of the lithium line at 6708 Å for the four coolest stars in our sample (HD 23362, K2V; HD 98800, K5Ve; HD 123160, G5V; HD 143006, G5Ve) we have found that HD 23362 has no detectable lithium at this wavelength. The upper limit of 15 mÅ corresponds to an abundance of log N(Li)<0.87, indicating that this star is probably a more evolved object than the rest of our sample, already well established on the main sequence. The lack of emission in its lines of Hα or Na I D support this conclusion. The lithium abundance of log N(Li)$\simeq$2.31 for HD 123160 is consistent with that found for stars of similar type in the Pleiades by Soderblom et al. (1993), implying that HD 123160 is around 70 Myr old. HD 143006 showed a particularly high lithium abundance of log N(Li)$\simeq$ 3.25, a value which is bracketed by those found in the Taurus–Auriga group by Padgett (1990). The age of this group was estimated to be 1 Myr by Kenyon et al. (1990) and it is likely that the age of HD 143006 is close to this figure. HD 98800 was also studied, although the three spectroscopic components of this system were not fully resolved. The two primary components (Aa and Ba, using the nomenclature of Torres et al. 1995) have been partially resolved in the Li 6708-Å line, enough to make an estimate of the contribution to the line by the Ba component. The intrinsic equivalent widths we found were similar to those found by Soderblom et al. (1996) for component Aa, but significantly higher for component Ba. This is attributed to the fact that Soderblom et al. (1996) were able to resolve all three components, whereas only the two brightest components were resolved in our spectrum. The abundances of log N(Li) $\simeq$ 2.91 and 2.35 derived by us for components Aa and Ba respectively show that both stars may be very young.

The emission-line characteristics of all the stars in our sample were studied, comparing them with those of other young objects, namely the HAe/Be stars and the T Tauri stars. Two stars, HD 161868 (γ Oph) and HD 216956 (α PsA), show no indication of emission. These two stars are MK standard stars: they are well established on the main sequence, and are likely to be significantly older than the rest of our sample. Of the rest of the A-type stars, two showed a single-peaked profile in their Hα line (HD 139614 and 169142), four showed a double-peaked structure (HD 35187, 141569, 142666 and 158643), and one a P Cyg profile (HD 144432). Of those that showed a double-peaked Hα profile, one (HD 142666) was close to a P Cyg profile, and one (HD 35187) had shown significant variability from the previous observations of Grady et al. (1996) and Zuckerman (1994). The remaining two stars (HD 141569 and 158643), which exhibited the more classical double-peaked profile, had the highest v sin$i$ values of the active sample, and it is likely that we see these stars close to edge-on. The two stars with a single-peaked Hα profile (HD 139614 and HD 169142), have the lowest v sin$i$ values of the active A-type sample, and it is possible that we are seeing these stars closer to pole-on than to edge-on. It is also interesting to note that these two stars also show an underabundance in Si and Mg (Dunkin et al. 1997a). With the exception of HD 141569, 161868 and 216956, all the A-type stars show unusual absorption or emission features in their He I line at 5876 Å. A-type stars are expected to show no detectable He I feature at this wavelength. Again, HD 35187 shows variability in the He λ5876 line from the previous observations of Grady et al. (1996). Variability in optical features is well known in HAeBe stars, and this star has previously been studied as an HAeBe star by Grady et al. (1996), amongst others. As well as HD 35187, HD 141569, 142666 and 144432 have all been classified as HAeBe stars or candidate members of the class by Thé et al. (1994). This highlights the spectral similarities between the early-type Vega-like stars and their younger counterparts, the HAeBe stars. Varying levels of activity in the Na I D line of our A-type stars was also found.

Of the later type stars (F4 to K5), HD 23362 showed no sign of emission in its Hα, Ca II triplet or Na I D lines. This star also had no detectable surface lithium, and, as already mentioned, it is probably a more evolved object, already on the main sequence. HD 123160, which had a relatively low surface lithium abundance, also showed little signs of activity. Other than a small Ca II K core emission, this star was inactive. HD 143006 (which showed a high surface lithium abundance) showed, in contrast, extensive emission in Hα and Ca II K, H and IR triplet lines. Similarly, HD 98800, which had a high lithium abundance, also showed activity in these lines. The hottest star in our later type sample (HD 135344, F4Ve) showed single-peaked emission in Hα and Hβ, and core emission in its Na I D line. HD 143006 also showed narrow emission spikes in its spectrum. This, coupled with its activity and youth implied by its lithium abundance, would suggest that HD 143006 is a good candidate to be a T Tauri star, again highlighting similarities between Vega-like stars and their pre-main-sequence counterparts.

We also searched for optical circumstellar lines in the spectra of our stars. Of the 14 stars studied, narrow absorption features were detected in the spectra of seven. All stars had lines that were of interstellar origin with the exceptions of HD 158643 and 144432, which appear to have circumstellar contributions to the observed lines. HD 158643 has had its narrow absorption features studied in detail before (e.g. LH90), but we have been able to assign a definite circumstellar origin to at least part of the absorption seen in its Ca II K core, as we have detected narrow absorption features in excited-state lines of Fe II lines that would not be seen in the interstellar medium. HD 144432 shows a possible narrow absorption feature in the core of the absorption trough in its Na I D profile. With a heliocentric velocity in excess of 90 km s^{-1}, this feature is also likely to be circumstellar.

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