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A search for circumstellar gas around normal A stars and Lambda Bootis stars*

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Abstract. We have searched for interstellar or circumstellar absorption lines in the center of Ca II K towards bright A-type stars that are mostly within 80 pc of the Sun. Narrow absorption features are found in about 30 % of the 28 normal main-sequence A stars and 18 metal-deficient λ Bootis stars studied.

We have determined surface gravities and projected rotational velocities. Most of the stars with detectable Ca K features have comparatively *low gravities* and *high projected rotational velocities*. This correlation with stellar properties implies that most of the narrow absorption features are of circumstellar rather than interstellar origin. The preference of low gravity and rapid rotation furthermore suggests that most of the gas shells around A stars develop in the pre-main-sequence phase of evolution, and disappear largely before the star arrives at the ZAMS.

Among the normal A stars studied, about 50 % are known to have *dust disks*. Unlike A stars with circumstellar gas, these dusty stars do not prefer low $\log g$ and high $v \sin i$. This results in an apparent lack of correlation between gas and dust, and indicates that normal A stars with gas shells and those with dust disks are not in the same evolutionary stage. We conjecture that dust disks tend to develop after most of the gas has disappeared.

Key words: stars: circumstellar matter – ISM: atoms, ions – stars: rotation – stars: pre-main sequence – stars: individual: β Pic

1. Introduction

The occurrence of *circumstellar dust* around A-type stars is a well-studied phenomenon. Since the discovery of a dust shell around Vega (Aumann et al. 1984) and the first optical observation of the dust disk around β Pictoris (Smith & Terrile 1984) numerous searches have been made through the IRAS database for main-sequence stars with infrared excesses, but only two of them are based on the IRAS Faint Source Survey which provides the best limiting sensitivity available. The survey by Cheng et al. (1992) presents an almost volume-limited sample of 'dusty' main-sequence A stars on which the present work is based. In a more recent evaluation of Faint Source Survey data, Mannings & Barlow (1998) extend the sample of 'Vega-like' objects towards other spectral types and luminosity classes.

The detection of *circumstellar gas*, on the other hand, usually is based on high-resolution spectroscopy of the delicate signature it imprints on the photospheric spectrum, narrow absorption features in the cores of strong photospheric lines of low excitation. The first detection of circumstellar lines ('shell spectra') in A-type stars seems due to Abt & Moyd (1973), who suggested that these shell stars are the A-type counterparts of the Be stars. Slettebak (1975) noticed that β Pic shows strong, narrow absorption components of Ca II H and K centered within the normal, broadened stellar H and K lines. Slettebak concluded that they are evidently of interstellar or circumstellar origin. In a comprehensive search for circumstellar lines in candidate β Pic-type stars, Lagrange-Henri et al. (1990) collected high-resolution spectra of the Ca K and Na D lines for A-type stars with known shell characteristics or infrared excesses (according to IRAS Point Source Catalog data). Among 49 objects, six showed β Pic-type absorption components. Although the survey was based mostly on bright, nearby stars, a potential *interstellar* origin of the narrow features remained an intriguing open question. In turn, investigations of the nearby interstellar gas may be complicated by the presence of *circumstellar* gas around a target star, a problem encountered in a recent ultra-high resolution K-line study (Crawford et al. 1998). The 'interstellar vs. circumstellar' issue will be raised again in Sect. 6 of the present paper.

In a previous paper (Holweger & Rentzsch-Holm 1995, hereafter HRH) we have studied the connection of circumstellar gas, surface chemistry, and rotation in metal-deficient A stars (λ Bootis stars) and in a small number of chemically normal A stars with infrared excesses. The present paper extends this study to essentially all positive IRAS detections in the Cheng et al. (1992) list of nearby A stars, as far as observable from ESO, Chile. It also includes negative detections to permit a differential study. In addition, the sample of λ Boo stars is extended.

The present study differs from that of Abt & Moyd (1973) in several respects. Their survey of shell spectra focuses on Am and normal A5-A9 IV stars while our samples extend from B9.5 V to A7. In addition, it has now become possible to include metal-

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* Based on observations collected at the European Southern Observatory, La Silla, Chile

deficient A stars of the λ Boo type and to distinguish between stars with and without dust disks. Compared to photographic spectroscopy CCD detectors now permit us to achieve higher S/N values at higher spectral resolution, which is very helpful for identifying weak, narrow absorption features. The Abt & Moyd (1973) sample, observed from Kitt Peak, has only two stars in common with our list, HR 10 and HR 7557. With respect to interpretation, Abt & Moyd discussed their results exclusively in terms of *post*-main-sequence evolution and suggest that most of the shell stars occur when the stars have depleted most of their hydrogen. By contrast, we argue that *pre*-main-sequence evolution is a more likely alternative (Sect. 6.1).

2. The stellar samples and basic parameters

2.1. Sample I: λ Bootis stars

This is an extended version of the HRH sample of metal-deficient A stars, which was based on λ Bootis stars catalogued by Gray (1988). It now comprises all confirmed members of this group listed by Gray & Corbally (1993) with the exception of three fainter stars beyond the limit of the Bright Star Catalogue (Hoffleit & Jaschek 1982, BSC).

We have obtained ESO high-resolution spectra of the Ca K line region in all objects except four at northern declinations. Fortunately, literature data are available for all of them, including the prototype λ Boo. Details are given in Sect. 4.

We note that Hauck et al. (1998) have carried out an independent search for λ Boo stars with shell characteristics, focusing on northern objects observed from Haute Provence Observatory. Their sample naturally differs from ours, and is based on a variety of lists of suspected members of the λ Boo group of stars, including that of Gray (1988). K-line data have been scrutinized by both studies in two stars, HR 1570 and HR 4828. In both cases we confirm the absence of narrow absorption features reported by Hauck et al. (1998).

2.2. Sample II: normal A stars

This is derived from the almost volume-limited sample of main-sequence A stars on which Cheng et al. (1992) have based their search for stars with circumstellar dust, using data from the IRAS satellite. In contrast to sample I, these A stars are not metal-deficient but appear chemically normal. A few of them, including Sirius (HR 2491), show marginal Am characteristics. This sample will be referred to as 'normal A stars' in the present paper.

We have recorded the spectral region around Ca II K at high-resolution in all stars classified as 'dusty' or 'not dusty' in Table 1 of Cheng et al. (1992), as far as they are observable from ESO, Chile. Borderline detections are not considered. We have also observed the dusty stars HR 5367 (HD 125473) of their sample II, and two A stars identified as dusty in other papers, HR 10 (Cheng et al. 1991), HR 4796 (Jura 1991), as well as the B9.5 Ve star HR 6519 (51 Oph, Grady & Silvis 1993). In addition, our sample includes two northern objects from the Cheng et al. list with published K-line data. These are HR 4295 and the prototype dusty A star Vega (HR 7001).

2.3. Basic stellar parameters

The two samples are listed in Table 1. Visual magnitudes, spectral types and duplicity data are from the BSC, while distances are based on HIPPARCOS data (ESA 1997).

Stellar parameters $T_{\rm eff}$ and $\log g$ were derived from Strömgren photometry (Hauck & Mermillod 1990), using the calibration of Napiwotzki et al. (1993).

3. Observations, data reduction, and spectrum synthesis

High-resolution CCD spectra were obtained with the ESO CES system in two observing periods (1996 February 26-March 2, and 1997 September 13–17). The instrumental setup was the same as in the earlier observations (see HRH) except that a somewhat higher resolving power (70 000 instead of 50 000) was chosen.

Data reduction and spectrum synthesis of the K-line region were carried out as outlined in HRH. If a narrow absorption feature was detected at the bottom of a stellar Ca K line, its equivalent width $W_{\rm K}$ was measured with respect to the photospheric line core. Results are given in Table 1. Upper limits are quoted in cases where no narrow feature was found. Depending on the S/N ratio achieved, upper limits vary from star to star. Examples showing positive and negative detections are depicted in Figs. 2–9 of HRH. In three normal A stars more than one absorption component was found (see Sect. 4.2).

In addition to Ca K we have also observed the Na D lines in those normal A stars that showed indications of narrow absorption features in Ca K, and in some of the λ Boo stars. The Na D spectral region contains numerous telluric H_2O lines. We have removed them from the stellar spectrum in the usual way, dividing the 'contaminated' stellar spectrum by the spectrum of a close-by reference star whose D lines are either very weak or broad and shallow, like that of a rapidly rotating O or B star.

The equivalent width, $W_{\rm D}$, quoted in Table 1 is the mean of Na D_1 and Na D_2. The line strength ratio $W_{\rm D}/W_{\rm K}$ is commonly used to discriminate between an interstellar or circumstellar origin (Sect. 6.6).

4. Remarks on the Ca K data of individual stars

4.1. The Ca K line in λ Bootis stars

The majority of λ Boo stars in Table 1 has already been investigated by HRH on the basis of ESO observations made in 1990, 1993, and 1994. The respective HR numbers are: 12, 541, 4828, 4881 (see also the comment at the end of this section), 7400, 7764A, 7764C, 8203, and 8437, and we have adopted the Ca K line data ($W_{\rm K}$ and $v \sin i$) quoted in Table 3 of HRH. The only exception is the binary HR 7959 / HR 7960, whose components we now have listed separately, taking their individual rotational velocities from Stürenburg (1993). As mentioned in Sect. 4.9 of HRH, the K line of this λ Boo binary could be observed only in

Table 1. Parameters of λ Bootis stars (sample I) and normal A stars (sample II).

HR	Name	HD	m_v	Spectral Type	d (pc)	$T_{\rm eff}$ (K)	$\log g$ ($\mathrm{cm\,s^{-2}}$)	$v \sin i$ ($\mathrm{km\,s^{-1}}$)	dusty?	$W_{\rm K}$ (mÅ)	$W_{\rm D}$ (mÅ)
Sample I											
12		319	5.94	A3 V	80.3	8140	3.80	60	–	<2	–
541		11413	5.94	A1 V	74.8	7950	3.83	122	–	18	–
1525		30422	6.19	A3 IV	57.5	7970	4.09	115	–	<1	<1
1570	π^1 Ori	31295	4.65	A0 V	37.0	9080	4.12	115	yes	<1	<1
1989	131 Tau	38545	5.72	A3 Vn	129.5	8970	3.60	200	–	72	–
4828	ρ Vir	110411	4.88	A0 V	36.9	9210	4.24	166	yes	<3	<1
4881		111786	6.15	A0 III	60.2	7440	3.96	126	–	44	86
5351	λ Boo	125162	4.18	A0 p	29.8	8920	4.11	105	yes	<2	–
5930		142703	6.13	A2 III	52.9	7200	3.98	98	–	<2	<1
7400	35 Aql	183324	5.80	A0 V	59.0	9260	4.22	90	–	<8	–
7736	29 Cyg	192640	4.97	A2 V	41.0	7990	3.99	80	yes	–	–
7764A		193281	6.30	A2 III	218.3	8080	3.58	83	–	<4	–
7764C		193256	7.40	A2 IV	218.3	7860	3.74	240	–	30	–
7959		198160	6.59	A2-3 IV-V	73.2	7970	3.98	200	–	5	–
7960		198161	6.59	A2-3 IV-V	73.2	7970	3.98	180	–	5	–
8203		204041	6.46	A1 IV	87.3	8100	4.03	65	–	<2	–
8437		210111	6.37	A2	78.7	7450	3.75	55	–	<4	–
8947	15 And	221756	5.59	A1 III	71.6	9020	3.91	100	–	<2	–
Sample II											
10		256	6.19	A6 Vn	160.3	7850	3.45	265	yes	105	2
553	ι Ari	11636	2.64	A5 V	18.3	8370	4.13	60	no	<1	<1
804	γ Cet	16970	3.47	A3 V	25.1	9230	4.06	165	no	<1	<1
1483		29573	5.01	A2 IV	69.7	8930	3.90	25	yes	<1	<1
1666	β Eri	33111	2.79	A3 III	27.2	8100	3.58	180	no	<1	<1
2020	β Pic	39060	3.85	A5 V	19.3	8200	4.24	132	yes	240	6
2491	α CMa	48915	-1.46	A1 Vm	2.6	10130	4.31	18	no	<1	<1
2550	α Pic	50241	3.27	A7 IV	30.3	7530	3.48	205	no	3	<2
2763	λ Gem	56537	3.58	A3 V	28.9	8480	3.91	150	no	<1	<1
3485	δ Vel	74956	1.96	A1 V	24.5	9250	3.79	178	no	26	4
3615	α Vol	78045	4.00	A2-3 IVm	38.1	8300	4.13	45	yes	<1	<1
3685	β Car	80007	1.68	A2 IV	34.1	9090	3.08	133	no	3	<2
3863		84121	5.32	A3 IV	67.3	7960	4.07	40	yes	<2	<2
4295	β UMa	95418	2.37	A1 V	24.4	9600	3.83	39	yes	<6	–
4534	β Leo	102647	2.14	A3 V	11.1	8630	4.21	110	yes	<1	<1
4796		109573	5.80	A0	67.1	10270	4.45	150	yes	3	3
5028	ι Cen	115892	2.75	A2 V	18.0	9400	4.10	85	no	<2	<1
5367	ψ Cen	125473	4.05	A0 IV	75.8	10250	3.71	132	yes	4	5
5531	α^2 Lib	130841	2.75	A3 IV	23.7	8240	3.95	80	no	<1	<1
6378	η Oph	155125	2.43	A2 V	25.8	8850	3.88	19	no	<1	<1
6519	51 Oph	158643	4.81	B9.5 Ve	130.7	9930	3.09	272	yes	23	18
6549	π Ara	159492	5.25	A5 IV-V	42.2	8190	4.25	41	yes	<1	<1
6556	α Oph	159561	2.08	A5 III	14.3	7960	3.62	210	no	22	3
7001	α Lyr	172167	0.03	A0 Va	7.8	9540	3.98	22	yes	<4	–
7557	α Aql	187642	0.77	A7 V	5.1	7890	4.02	208	no	<2	<1
7779	κ^1 Sgr	193571	5.59	A0 V	74.9	9860	4.32	71	yes	<2	<2
8322	δ Cap	207098	2.87	A Vm	11.8	7410	4.13	87	no	<1	<2
8728	α PsA	216956	1.16	A3 V	7.7	8760	4.21	75	yes	<2	<2

combined light, hence the equivalent width quoted in Table 1 is actually the mean of both components.

Evaluation of the new ESO observations provided data for three additional λ Boo stars, HR 1525, HR 1570 (π^1 Ori), and HR 5930 (HD 142703). Neither star shows indications of narrow structure in the core of the K line.

Finally, the Gray & Corbally (1993) list of confirmed λ Boo stars includes four northern BSC objects, HR 1989

(131 Tau), HR 5351 (the prototype λ Boo), HR 7736 (29 Cyg), and HR 8947 (15 And). The respective entries in Table 1 are derived from literature data as follows.

HR 1989, HR 7736, and HR 8947 have been analyzed by Stürenburg (1993), whose results for $v \sin i$ are adopted here. Ca K spectra were not available at that time.

HR 1989 shows prominent shell features in the visible spectrum, as first noticed by Stürenburg (1993, see his Fig. 11). This has been confirmed by Bohlender & Walker (1994), who conclude that narrow absorption lines are present in the cores of Ca II H and K, and the Balmer lines. Hauck et al. (1998) show a high-resolution profile of Ca K with a prominent central absorption (see their Fig. 1f) which they attribute to a circumstellar shell. According to Hauck et al., its equivalent width amounts to 72.2 mÅ. We adopt their result, noting that the absorption feature of HR 1989 is the strongest of the entire sample (and of the Hauck et al. sample as well).

HR 5351 has been observed by Hauck et al. (1998). A high-resolution spectrum of Ca K is depicted in their Fig. 3. The line profile does not show any narrow structure in the core, but Hauck et al. point out that faint emission humps might be present in its outer parts. We have evaluated the Ca K profile to derive $v \sin i$ and to estimate an upper limit for $W_{\rm K}$.

HR 7736 has been annotated by Stürenburg (1993) as displaying weak shell features, but no illustration is given. Inspection of the spectra shown in his earlier work (Stürenburg 1992) does not confirm the presence of shell-type line cores. We conclude that the detection is marginal, and count HR 7736 as one of the λ Boo stars with negative detections, at the sensitivity level achieved here.

HR 8947 is also among the stars surveyed by Hauck et al. (1998). No shell features have been detected, in agreement with Stürenburg (1993). We have adopted the same upper limit for $W_{\rm K}$ as for HR 5351.

Finally, we note that HR 4881 has an unresolved companion of early spectral type F that contributes to the longer wavelength part of the spectrum (Faraggiana et al. 1997). Faraggiana et al. argue that the main contribution to the narrow absorptions in the spectrum of HR 4881 is due to the F star. This is certainly true for metal lines of intermediate strength. But the superposition of the Ca K line of the λ Boo star with that of an early F star, which is much stronger and broader, cannot produce an absorption feature as narrow and strong as that observed in HR 4881. This may be seen by comparing the K line in Fig. 2 of HRH with that of α CMi (F5 IV-V) reproduced in the Procyon atlas (Griffin & Griffin 1979). We conclude that the Ca K feature in HR 4881 must be of circumstellar or interstellar origin.

By contrast, the Na D lines are much narrower in F stars than in an A star like HR 4881. Surprisingly, each of the two Na D lines in HR 4881 exhibits *two* absorption components clearly separated by 0.7 Å (35 km s^{-1}) and of similar strength (the value quoted in Table 1 refers to the sum of both), while the Ca K feature has always been found single (cf. Fig. 5 of HRH). The binarity of HR 4881 may explain this puzzle. Since the F-type companion contributes mainly to the longer wavelength part of the visible spectrum, one of the two narrow Na D absorption doublets is probably due to the F star. Indeed, the radial velocity of one doublet agrees with that of the Ca K absorption, hence it is probably also of interstellar or circumstellar origin. The other one is more redshifted and also somewhat broader, consistent with the D-line profiles of an F star like Procyon.

4.2. The Ca K line in normal A stars

Apart from two stars at northern declinations, all of the positive and negative IRAS detections listed in sample II of Table 1 have been observed in the 1996 and 1997 ESO observing campaigns. Six of the dusty A stars have already been studied preliminarily by HRH using earlier ESO observations. The Ca K results quoted in Table 1 are derived from the new 1996/1997 data.

For the two northern objects in Table 1, HR 4295 (β UMa) and Vega (HR 7001), published data are available.

HR 4295 has been observed by Hobbs (1986) in a search for gas around 6 A-type and 4 F-type stars with infrared excesses, based on high-resolution Digicon spectra of Ca K recorded at McDonald Observatory. No narrow absorption features were found, and an upper limit of 5.5 mÅ is quoted. For $v \sin i$ we have adopted the value given in the BSC.

Vega, the prototype of dusty A stars, was observed earlier with the same equipment (Hobbs et al. 1985). No structure could be detected in the core of Ca K. The upper limit was 4.0 mÅ in this case. The entry for $v \sin i$ in Table 1 is from Gulliver et al. (1994).

Finally, we mention three stars whose Ca K line shows more than one narrow absorption component in our ESO spectra. These are HR 10, HR 2020 (β Pic), and HR 4796. The former two are known to show circumstellar features consisting of a variable component and a seemingly stable central absorption (Welsh et al. 1998; Beust et al. 1998). The equivalent width quoted in Table 1 refers to the main component only. The third, HR 4796, shows a main component close to the center of the photospheric line, and a weaker one displaced by about 10 km s^{-1} towards shorter wavelengths. Like HR 10 and β Pic this otherwise normal A star has a massive circumstellar dust disk (Sect. 6.1). A *circum*stellar origin of at least one of the components in HR 4796 is highly probable. Since nothing is known about a possible variability in Ca K we quote the equivalent width of both narrow features combined.

5. The $\log g$ - $T_{\rm eff}$ diagram as a useful diagnostic for stellar evolution near the main sequence

Fig. 1 shows theoretical evolutionary tracks in the $\log g$ - $T_{\rm eff}$ plane. Representations of this kind are used below as a substitute for the conventional HRD. This deserves some comments. The HRD involves *luminosity* or absolute magnitude as the prime indicator of radius and its change with evolution. For the diagnosis of evolutionary phases, in particular near the main sequence, we consider *surface gravity* as a useful alternative for three reasons.

(1) Because g is a purely spectroscopic quantity, it can be determined without knowledge of the stellar parallax. An example is the evolutionary stage of β Pic. As noted by HRH (Sect. 6.5),

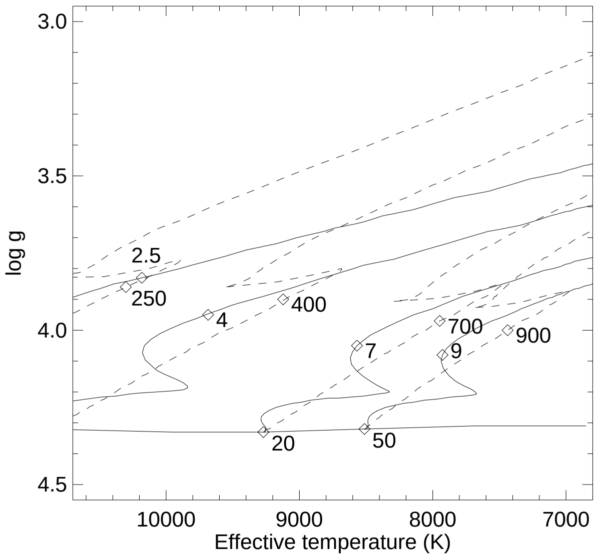

Fig. 1. Evolutionary tracks in a $\log g$ - $T_{\rm eff}$ diagram whose axes are chosen analogous to a Hertzsprung-Russell diagram. Shown are pre-main-sequence and main-sequence models of Siess et al. (1997). The evolution towards and off the main sequence is represented by continuous and broken lines, respectively, for models of mass 3, 2.5, 2, and 1.8 $M_{\odot}$ (from top to bottom). The numbers along the tracks denote the age (in 10^6 yr), counted from the stellar birthline through the main sequence and later stages. No convective core overshooting is assumed in these models.

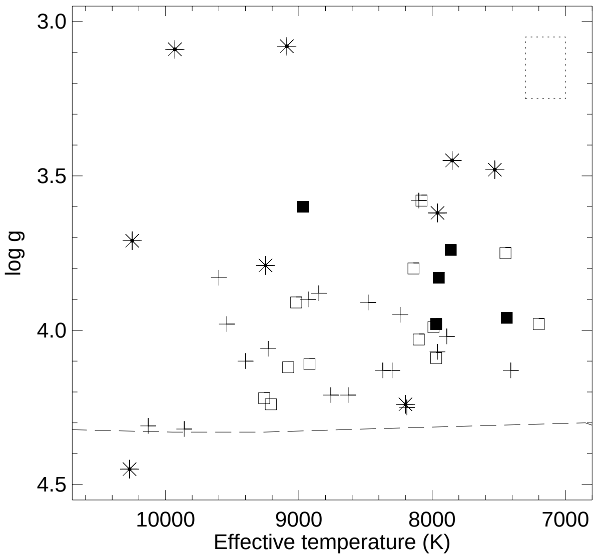

Fig. 2. Normal A stars (crosses and asterisks) and λ Boo stars (open and filled squares) in the $\log g$ - $T_{\rm eff}$ diagram. Stars with a narrow absorption feature in the center of Ca K are shown as asterisks (normal A stars) and filled squares (λ Boo stars), respectively. The dashed line denotes the zero-age main sequence for masses between 2.3 and 1.4 $M_{\odot}$. An error box in the upper right corner indicates the internal accuracy.

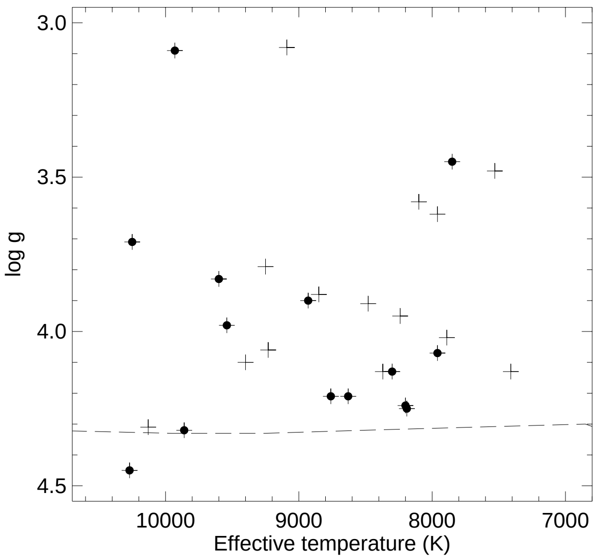

Fig. 3. The same normal A stars shown also in Fig. 2, but now grouped according to infrared excess rather than narrow Ca K absorption. Normal A stars without detectable dust emission are denoted by crosses, while those classified as ‘dusty’ are overplotted with filled circles. Not shown are λ Bootis stars; most of them probably are dusty (see text). The dashed line is the zero-age main sequence.

its position in the $\log g$ - $T_{\rm eff}$ diagram clearly places this star on the ZAMS, a result that has been confirmed subsequently when HIPPARCOS parallaxes became available (Crifo et al. 1997).

(2) Since $g \propto R^{-2}$, while $L \propto R^2\,T_{\rm eff}^4$, gravity is a more direct measure of radius than luminosity is. This becomes important near the main sequence in either pre- or post-main-sequence evolution, when contraction (or expansion) usually is connected with rising (or decreasing) temperature which it tends to cancel the effect of the radius change in L, but not in g.

(3) The luminosity assigned to an unresolved binary whose components are of similar spectral type will exceed the true stellar luminosity by a factor of two, while their combined spectrum resembles that of either component and hence leads to the correct spectroscopic gravity.

Considering the uncertainties involved in practice, we prefer to use the $\log g$ - $T_{\rm eff}$ presentation for discussing evolutionary aspects. A conventional HRD showing most of the stars of sample II is also available (Hempel et al. 1998).

6. Results and discussion

6.1. *Narrow absorption features in normal A stars and λ Bootis stars*

Among the 28 normal A stars searched for Ca K features, 9 (32 %) are positive detections (Table 1). Among λ Boo stars the incidence of Ca K features is likewise high, yielding 5 detections in a sample of 17 stars (29 %, counting HR 7959/HR 7960 as one star). We note that 85 % of our stars are located within 80 pc of the Sun.

In Fig. 2 both samples of A stars are plotted in a diagnostic $\log g$ - $T_{\rm eff}$ diagram that reveals some interesting features. If stars with and without narrow absorption are considered separately, their distributions turn out to be remarkably different. Stars without Ca K features (shown as crosses and open squares in Fig. 2) are almost exclusively located in the lower half of the diagram. In turn, *narrow Ca K features are preferentially found among the lower gravity stars* of either sample.

Two remarkable exceptions from the latter rule are HR 4796 (the star located below the ZAMS) and β Pic (slightly above the ZAMS at $T_{\rm eff} = 8200$ K). While β Pic shows conspicuous narrow absorption in Ca K that is well documented in the literature, that of HR 4796 is weak (see Table 1) and, to our knowledge, has not been noticed before. Interestingly, these otherwise normal A stars are also outstanding *dusty* objects: HR 4796, like β Pic, has a massive dust disk whose thermal emission has been spatially resolved at mid-infrared wavelengths (Jayawardhana et al. 1998, Koerner et al. 1998). This suggests that both stars do not conform to the rule deduced from the lower gravity stars simply because their circumstellar disks contain more dust *and gas* than is typical for dusty A stars close to the ZAMS.

What is the evolutionary stage of the normal A stars and the λ Bootis stars depicted in Fig. 2? Comparison with theoretical tracks in Fig. 1 shows that only a few are true main-sequence objects, among them the just mentioned prominent disk stars HR 4796 and β Pic. Most stars of both samples are located clearly *above* the ZAMS. Which of them are pre-main-sequence objects, and which have already left the ZAMS and are on the way to the red giant branch?

Post-main-sequence evolution implies quite long timescales (Fig. 1). More specifically, narrow absorption features in Ca K would not show up before these intermediate mass stars are several 10^8 yr old and have already evolved off the main sequence.

In our opinion the pre-main-sequence alternative is more plausible. We propose that the narrow absorption lines detected in stars significantly *above the ZAMS* originate in gas shells surrounding *pre-main-sequence objects* that are in the final phase of protostellar contraction. In the case of λ Boo stars this view is supported by the discovery of λ Boo stars in OB associations (Gray & Corbally 1993; Paunzen & Gray 1997), and it fits well into the accretion model proposed to explain their metal deficiency (Venn & Lambert 1990). The time scales involved are on the order of 10^6 - 10^7 yr (Fig. 1). The paucity of stars with circumstellar shells closer to the ZAMS then implies that in most cases the gas has disappeared when the star arrives on the main sequence.

Our interpretation contrasts with that of Abt & Moyd (1973) who do not consider *pre*-main-sequence evolution at all, possibly because appropriate theoretical tracks were not available at that time. Abt & Moyd suggest that most of the A5-A9 IV stars with shell spectra have already depleted most of their hydrogen and are in what they call the 'overall contraction phase' (which means contraction of the stellar core rather than pre-main-sequence contraction).

In any case, the mere fact that the presence, or absence of the narrow absorption features in the photospheric Ca K line is clearly correlated with intrinsic stellar properties – $\log g$ and $T_{\rm eff}$ – strongly suggests that they *originate in the stellar environment* rather than in interstellar space.

6.2. *Dust disks and narrow absorption features: normal A stars*

One might expect that dust disks are generally accompanied by circumstellar gas, like in the prominent cases of β Pic and HR 10 (Sect. 4.2). However, comparison of Fig. 3 with Fig. 2 shows that the real situation is remarkably different.

In contrast to stars with and without narrow Ca K features, whose tendency to segregate in the $\log g$ - $T_{\rm eff}$ plane we have disussed in the preceding section, A stars with and without dust disks are distributed more uniformly. Dusty stars do not prefer lower gravities as stars with Ca K features do, rather the opposite behavior is indicated. As a consequence of these different distributions, a lack of correlation between dust and Ca K features is indicated: among the 14 normal A stars with dust disks listed in Table 1, only 5 show detectable narrow Ca K features while 9 do not. Clearly more data are highly desirable in order to improve the statistical significance of this remarkable result.

If taken for real, the difference in the distributions of stars with dust disks and with Ca K features may be explained in a simple way. Recalling the theoretical tracks shown in Fig. 1, the implication is that the two phenomena develop at somewhat *different evolutionary stages.* We have advocated in Sect. 6.1 that most of the Ca K features are due to circumstellar gas around pre-main-sequence stars. A lack of coincidence of dust and gas then suggests that (statistically) dust disks tend to develop *after* most of the gas has disappeared.

We note that A stars with dust disks and those with Ca K features also behave differently with respect to *rotation*, as outlined in Sect. 6.5.

6.3. *Dust around λ Bootis stars*

Data on dust emission from λ Boo stars are much more scarce than for normal A stars. To our knowledge infrared excesses have been detected in only four members of sample I. HR 1570 (π^1 Ori) and HR 5351 (λ Boo) were identified as 'Vega-like' by Sadakane & Nishida (1986), and HR 4828 (ρ Vir) is among the dusty A stars listed by Cheng et al. (1992). Waters et al. (1992) have added HR 7736 (29 Cyg) to this small list.

Because the data for λ Boo stars appear rather incomplete we have not included them in Fig. 3. However, we have noticed that these four dusty λ Boo stars are just the *brightest* ones of sample I, with visual magnitudes brighter than $V = 5$. Therefore we suspect that *most λ Boo stars actually have dust disks* but are too far away to permit unambiguous detection of their infrared excesses.

6.4. *Narrow absorption features and rotation*

Spectrum synthesis of the photospheric Ca K line of A stars permits an accurate determination of their projected rotational velocities, $v \sin i$ (for an illustration of the effect of rotation and calcium abundance on the Ca K profile see Fig. 1 of HRH). The $v \sin i$ values adopted here are listed in Table 1; most of them have been determined in this study and in HRH (see Sect. 4).

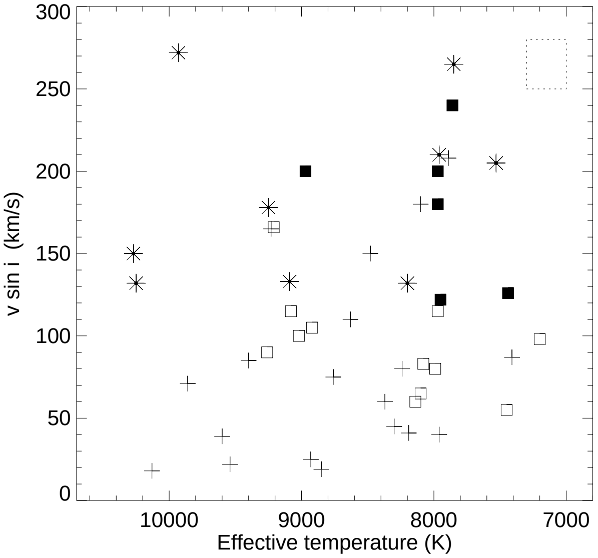

Fig. 4. Projected rotational velocity vs. effective temperature for normal A stars and λ Boo stars with and without narrow Ca K features. The symbols have the same meaning as in Fig. 2.

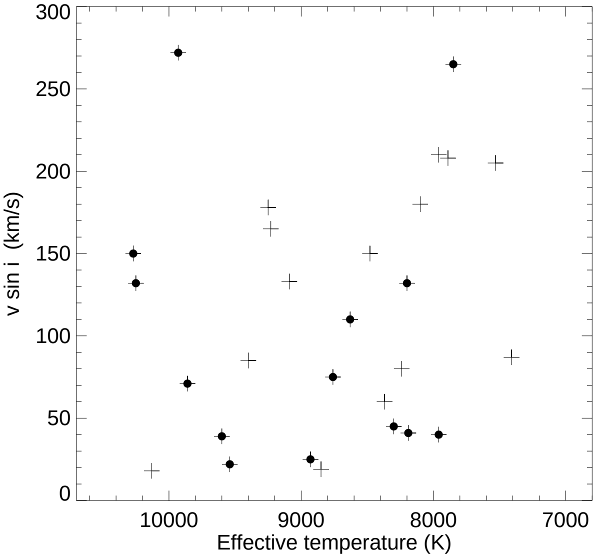

Fig. 5. Projected rotational velocity vs. effective temperature for normal A stars with and without dust disks. The symbols have the same meaning as in Fig. 3.

In Fig. 4 stars with and without narrow Ca K features are displayed in a $v \sin i$ - $T_{\rm eff}$ diagram. A preliminary version of this plot, based on a much smaller sample of stars, is given in Fig. 12 of HRH. It was concluded that rotation and narrow Ca K features are closely connected. Additional evidence was reported by Hauck et al. (1998). The more complete data set available now permits to substantiate this finding.

Fig. 4 shows that there is an *almost one-to-one correspondence between narrow Ca K features and rapid rotation* in both samples. While Ca K features are present in most stars in the upper half of the diagram, they are completely absent in the lower part. The mean $v \sin i$ following from 15 λ Boo stars and normal A stars *with* Ca K features is 183 km s^{-1}, while the mean derived from their 31 ‘featureless’ counterparts is only 86 km s^{-1}.

A possible objection against this statistics should be mentioned. In stars with low $v \sin i$ it may be difficult or impossible to identify interstellar or circumstellar features against the background of the *narrow photospheric* Ca K line profile. However, narrow interstellar absorption lines have been detected in stars whose $v \sin i$ is well below 20 km s^{-1} (cf. Vallerga et al. 1993), corresponding to the slowest rotators of our list. Close inspection of our own spectra shows that rotational broadening in stars with $v \sin i \approx 20$ km s^{-1} would easily permit identification of circumstellar or interstellar features in Ca K, if they were present. Of course, high spectral resolution is required for their unambiguous detection.

The fact that there is not a single star with narrow Ca K features whose projected rotational velocity is below 122 km s^{-1} has two important implications.

(1) Given the incidence of Ca K features in the *upper* part of Fig. 4, their complete absence below 122 km s^{-1} shows that stellar rotation is the prime factor that determines whether narrow absorption components are present or not. This provides compelling evidence that *interstellar lines contribute little, if any, to the observed features.*

(2) It is incompatible with a random orientation of $\sin i$ values, as was already suspected by HRH on the basis of a much smaller stellar sample. The most plausible explanations is that narrow absorption features in Ca K arise in *equatorial disks surrounding the rotating stars.* The column density of absorbing gas, and hence the probability of its detection, will have a pronounced maximum if the disk is viewed edge-on.

The same kind of reasoning was applied by Abt & Moyd (1973) in their study of 35 rapidly rotating A stars. Shell spectra were found in 8 of them (23 %), a fraction slightly smaller than that following from Table 1 (31 %, counting HR 7959/HR 7960 as one star). Probably the weakest features are below the detection limit set by photographic spectroscopy.

Finally, we note that the slow rotators in Fig. 4, with $v \sin i$ smaller than about 120 km s^{-1}, may include a few rapid rotators viewed nearly pole-on. Indeed, *Vega* (HR 7001) is such a rare case. While its $v \sin i$ value of 22 km s^{-1} is among the smallest of Table 1, detailed analysis of its box-shaped photospheric lines by Gulliver et al. (1994) has revealed its true equatorial velocity, $v = 245 \pm 15$ km s^{-1}.

6.5. *Dust disks and rotation (normal A stars)*

Fig. 5 shows $v \sin i$ for normal A stars. Stars with and without infrared excess are distinguished by different symbols. The distribution of the two groups looks different. *Dusty A stars appear to have systematically smaller* $v \sin i$, although they include the two fastest rotators of the entire sample. Mean $v \sin i$ values of 101 km s^{-1} and 127 km s^{-1} are derived from stars with and without dust, respectively.

If this difference is considered as significant, one might argue that it is a consequence of the viewing angle of the dust disks, in analogy to the case of Ca K absorption features discussed above. Disks viewed edge-on, corresponding to high $v \sin i$ stars in Fig. 4, will subtend smaller solid angles than pole-on disks. If emission occurs under optically thick conditions, the infrared flux received from edge-on disks will be smaller than that from pole-on disks. Statistically, the dust of high-$v \sin i$ stars will be more difficult to detect.

The crucial problem with this explanation is, however, that dust disks of normal A stars are considered to be optically *thin* (see, e.g., Aumann et al. 1984, Harvey et al. 1996). In this case the entire disk contributes to the observed infrared flux, not just its projected surface. Hence $\sin i$ is irrelevant for the detection of its infrared excess.

Probably another explanation for the smaller $v \sin i$ of the dusty stars has to be sought. We do not think that the problem can be solved on the basis of the present data set, but we wish to point out that a comparison of Fig. 5 with Fig. 4 shows a remarkable difference in the distributions of stars with dust and with narrow Ca K absorption which is analogous to that in the $\log g$ - $T_{\rm eff}$ plane discussed in Sect. 6.2. If dusty A stars indeed represent a later evolutionary phase than those with (circumstellar) Ca K features, as conjectured in Sect. 6.2, then the systematically different $v \sin i$ of both groups may provide clues to the rotational evolution towards, and on the main sequence. Clearly a closer investigation is called for.

6.6. Narrow absorption features: interstellar versus circumstellar origin

Both of our samples consist of bright stars, most of them (85 %) located within 80 pc of the Sun (Table 1). Nevertheless a potential interstellar origin of the narrow Ca K features cannot be ruled out without independent evidence, a major problem encountered by Lagrange-Henri et al. (1990) in their search for β Pic-like stars.

Direct evidence for circumstellar gas is the occurrence of *variable* absorption components in Ca K and other lines. The well-known examples β Pic and HR 10 have already been mentioned in Sect. 4.2. Table 1 also includes 51 Oph (HR 6519), a well-known shell star with variable circumstellar absorption studied extensively in the search for β Pic-like stars (e.g. Grady & Silvis 1993, Lecavelier des Etangs et al. 1997, Dunkin et al. 1997). All three stars have a massive dust disk. As noted in Sect. 4.2, HR 4796 also shows structure in Ca K and has a massive dust disk as well. Although nothing is known about a possible variability of the Ca K feature, it is likely that at least one of the narrow components detected is of circumstellar origin.

Indirect evidence has been reported in Sects. 6.1 and 6.4. It was found that the occurrence of narrow Ca K features is correlated with basic properties of the stars towards which they are observed, in particular with their gravity and projected rotational velocity. This finding strongly supports a circumstellar rather than interstellar origin of the narrow absorption lines, or at least a major circumstellar contribution. This kind of reasoning is applicable independent of distance.

Another criterion for a circumstellar origin, commonly applied in the literature (cf. Lagrange-Henri et al. 1990, Hobbs et al. 1985), requires that the equivalent width ratio, $W_{\rm D}/W_{\rm K}$, of the Na D lines and Ca II K should be well below unity. Inspection of Table 1 shows that several of the stars, whose narrow Ca K features we have attributed to circumstellar gas, do not obey this rule. Does this indicate an interstellar origin?

Among the exceptions is 51 Oph (HR 6519), whose variable absorption has just been mentioned as unambiguous evidence for the presence of circumstellar gas. Another exception is the cool λ Boo star HR 4881. Its strong absorption feature in Ca K (Table 1) has already been detected by Gray (1988), who notes that this bright star is in a region of the sky with negligible interstellar absorption, supporting a circumstellar origin. As noted in Sect. 4.1, the Na D equivalent width quoted in Table 1 includes a contribution of the F-type companion. If this is removed, the remaining narrow component still amounts to 44 mÅ, i.e. it is as strong as the Ca K feature and hence does not conform to the rule that $W_{\rm D}/W_{\rm K}$ should be well below unity. We conclude that deviations from the $W_{\rm D}/W_{\rm K}$ rule occur in some circumstellar disks, indicating a considerable rangeof ionization conditions or elemental abundances in the gas phase.

The referee has pointed out that the faintest Ca K features in our survey – four cases in sample II with $W_{\rm K}$ between 3 and 4 mÅ – could be due to the local interstellar cloud. As shown by Lallement et al. (1995) its signature can best be seen in UV lines of ions like Mg II and Fe II, which are the dominant stages of ionization in a typical warm cloud, while Ca is mostly Ca III. According to Lallement et al. (see also Ferlet et al. 1986) the Ca K absorption equivalent width due to the local cloud is only 1.7 mÅ in the case of α Aql (HR 7557), consistent with our upper limit of 2 mÅ (Table 1). This contrasts with 60 mÅ for Mg II and 15 mÅ for Fe II. Among the A-type stars listed in Table 1 of Lallement et al. (1995) α Aql has a higher than average interstellar Ca II column density, therefore local-cloud contributions to $W_{\rm K}$ in excess of 2 mÅ appear unlikely. Omitting the four stars with $W_{\rm K}$ = 3 and 4 mÅ (HR 2550, HR 3685, HR 4796, and HR 5367) altogether would not affect our conclusions about the preferential occurrence of narrow Ca K components among rapid rotators discussed in Sect. 6.4. In fact, these stars occupy the region of intermediate $v \sin i$ in in Fig. 4 and thus fit into the picture of a general correlation between $v \sin i$ and circumstellar absorption (see also Fig. 11 of HRH). In addition, HR 4796 is the star with a massive disk of dust which is likely to contain also some gas. Finally, it is hard to understand why *inter*stellar lines should occur only in stars rotating more rapidly than 130 km s^{-1}. Therefore we consider a purely interstellar origin of even the faintest Ca K features in our survey as improbable.

7. Conclusions

The main results of this work can be summarized as follows:

1. Narrow absorption lines in the core of the photospheric Ca K line are quite common in bright normal A stars as well as in

λ Boo stars. We find such features in about 30 % of both groups of A stars.

2. The occurrence of Ca K absorption features is correlated with stellar properties (gravity and rotation). We conclude that most of the Ca K features in our samples of bright A stars are of *circumstellar* rather than interstellar origin.

3. Specifically, circumstellar lines occur preferably in normal A stars and λ Boo stars with *low* gravities and *high* projected rotational velocities. We suggest that these stars are in the pre-main-sequence phase of evolution.

4. Unlike normal A stars with *circumstellar Ca K lines* those with *dust disks* do not prefer low gravities and rapid rotation. A possible explanation is that in the course of pre-main-sequence evolution dust disks tend to develop after most of the gas has disappeared. This and the question of rotational evolution deserves further study.

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