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LETTER

Letter to the Editor

The surface composition of Beta Pictoris*

H. Holweger[1], **M. Hempel**[1], **T. van Thiel**[1] **and A. Kaufer**[2]

[1] Institut für Astronomie und Astrophysik, Universität Kiel, D-24098 Kiel, Germany
[2] Landessternwarte Heidelberg-Königstuhl, D-69117 Heidelberg, Germany

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Abstract. We present an element-by-element analysis of the surface composition of β Pic (A5 V) based on high-resolution broad-band optical spectra. The abundances (relative to H) of C, Ca, Ti, Cr, Fe, Sr, and Ba are solar. Obviously β Pic does not show the 'λ-Boo phenomenon'—the metal deficiency of certain cool A-type stars attributed to accreting circumstellar matter.

Key words: Stars: abundances – atmospheres – formation – individual: Beta Pictoris – circumstellar matter

1. Introduction

Main-sequence A stars have shallow convection zones, therefore their surface composition is very sensitive to any 'contamination' by processes of diffusion or accretion. Diffusion is known to dominate in AmFm stars, while accretion of gas—after gas-dust separation—is thought to be responsible for the deficiency of refractory elements in λ Bootis stars (Venn and Lambert 1990). Support for the latter model comes from the exceptionally high incidence of circumstellar (CS) gas detected in λ Boo stars (Holweger and Rentzsch-Holm 1995, hereafter HRH95).

Does the prototype of A stars with CS dust and gas, β Pic, also show the λ Boo phenomenon? Conflicting results have been reported in the literature. Paresce (1991) derives a low metal abundance, [M/H] = -0.6 ± 0.3, from photometry. This result has led King and Patten (1992) to suggest that β Pic is an unrecognized λ Boo star. Contrary to this, Lanz et al. (1995) conclude that *HST* GHRS data are consistent with a solar metallicity.

In this paper we present the first element-by-element spectroscopic analysis of β Pic (Sects. 3 and 4) and discuss the results in the context of diffusion, accretion, and stellar evolution (Sects. 5 and 6).

Send offprint requests to: H. Holweger

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

2. Observations

The CCD spectra studied in this work have been obtained in February and March 1995 with the ESO 50-cm telescope equipped with the HEROS spectrograph developed at Heidelberg (Stahl et al. 1996). Its two channels cover the wavelength ranges 3450 Å – 5550 Å and 5820 Å – 8600 Å . The spectra were recorded at a resolving power of 20 000. Data reduction and wavelength calibration was carried out by one of us (A.K.) with a modified version of MIDAS.

3. Model-atmosphere analysis

Model-atmosphere analysis was carried out as outlined in a previous study of A-type stars (HRH95), adopting stellar parameters of β Pic derived from Strömgren photometry, $T_{\rm eff}$ = 8200 K, log g = 4.24. These values are in agreement with an independent determination by Lanz et al. (1995) based on a combination of Strömgren and Geneva photometry. We employ a model atmosphere calculated with the ATLAS9 code (Kurucz 1993), assuming solar metallicity.

To derive the metallicity and microturbulence of β Pic we use lines of Ti II, Cr II, and Fe II. Since iron-group elements are predominantly singly ionized in A-type stars, departures from LTE in the ionization equilibrium will hardly affect these ion lines, as demonstrated for the case of Fe I/II (Rentzsch-Holm 1996). The VALD data base (Piskunov et al. 1995) was used for selecting lines suitable for abundance analysis and for identifying perturbing lines of other elements. In view of substantial rotational broadening ($v \sin i$ = 132 km s^{-1} according to HRH95) detailed spectrum synthesis is indispensable.

The lines selected are listed in Table 1. Apart from C I the log gf values are from the VALD list. They are based on recent measurements for Ti II and Cr II and data from Kurucz' data base (CD ROM 18 and 20-22 issued 1993 and 1994) for Fe II, Sr II, and Ba II. For C I we take advantage of the new NIST compilation (Wiese et al. 1996).

The *element abundances* log $N_{\rm el}$ listed in Table 1 have been obtained by spectrum synthesis, assuming LTE. In each spectral window blends are taken into account as far as necessary, and the quantity $\log gfN_{\rm el}$ of each line in a window is adjusted iteratively until an optimum fit to the observed spectrum is achieved (see Stürenburg (1993) for examples). The *equivalent widths* quoted in the last column of Table 1 are theoretical quantities, derived from these $\log gfN_{\rm el}$ values for the idealized case of an isolated line, and serving as a measure of line strength. They are denoted less certain if the 'target' line is not the dominant contributor to a spectral feature (but is still clearly traceable).

The stellar *microturbulent velocity* ξ was determined as usual by comparing abundances derived from various lines of a given element and adjusting ξ to minimize their dependence on line strength. The number of iron-group lines is sufficiently large to permit independent determinations for Ti II, Cr II, and Fe II.

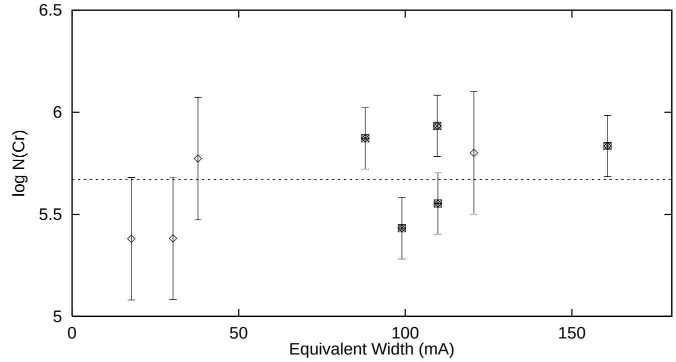

Fig. 1. Example illustrating abundance analysis. Chromium abundances derived from individual Cr II lines as a function of line strength. A microturbulence of $\xi = 4.0\ {\rm km\,s^{-1}}$ has been adopted. Diamonds denote lines with less reliable equivalent widths. The dotted line indicates the solar abundance.

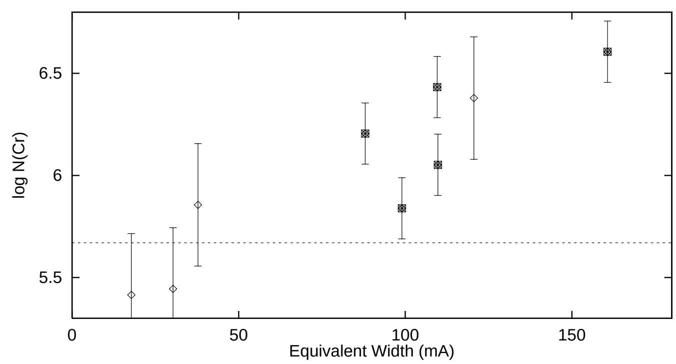

Fig. 2. Same as Fig. 1, but for $\xi = 2.0\ {\rm km\,s^{-1}}$. The trend appearing among the stronger lines indicates that the assumed microturbulence is too small.

4. Results

4.1 Microturbulence

The microturbulence parameter derived as outlined becomes $\xi = 4.0\ {\rm km\,s^{-1}}$, with an estimated uncertainty of $\pm 0.3\ {\rm km\,s^{-1}}$. Abundances resulting from individual lines are listed in Tab. 1. Figure 1 illustrates the case of Cr II; error limits shown are estimates based on the fit of observed and synthetic spectrum. Ti II and Fe II look similar, but the spread is somewhat larger. We suppose that the Cr II gf-values have the highest internal accuracy. The slight residual trend indicated in Fig. 1 is absent in Ti and Fe. Figure 2 shows the strong dependence on line strength that appears if a smaller microturbulence is used. Ti and Fe behave like Cr.

Recent literature data on microturbulence in cool A-type stars, although scarce, indicate vivid photospheric motions while standard mixing-length models (like ATLAS9) predict that convection is confined to subphotospheric layers. In a study of λ Boo stars with $T_{\rm eff}$ values between 7450 and 9260 K, Stürenburg (1993) has determined ξ values for five of them, leading to a mean value of $3.0 \pm 0.4\ {\rm km\,s^{-1}}$. The β Pic result therefore strengthens the view that convective motions penetrate into the line-forming layers, in accordance with radiation hydrodynamics models (Freytag et al. 1996).

4.2 Abundances

The lines listed in Tab. 1, supplemented by Ca K studied by HRH95, lead to the following *photospheric abundances of* β *Pic:*

$$\begin{array}{llll}
\log N_{\rm C} & = 8.59 \pm 0.16\,; & [{\rm C/H}] & = +0.03 \\
\log N_{\rm Ca} & = 6.38 \pm 0.20\,; & [{\rm Ca/H}] & = +0.02 \\
\log N_{\rm Ti} & = 4.74 \pm 0.35\,; & [{\rm Ti/H}] & = -0.25 \\
\log N_{\rm Cr} & = 5.68 \pm 0.22\,; & [{\rm Cr/H}] & = +0.01 \\
\log N_{\rm Fe} & = 7.64 \pm 0.30\,; & [{\rm Fe/H}] & = +0.13 \\
\log N_{\rm Sr} & = 3.03 \pm 0.30\,; & [{\rm Sr/H}] & = +0.13 \\
\log N_{\rm Ba} & = 2.22 \pm 0.30\,; & [{\rm Ba/H}] & = +0.09
\end{array}$$

with the usual normalization $\log N_{\rm H} = 12$. The quoted error limits are standard deviations except for Ca, Sr and Ba where an estimate based on the quality of the line profile(s) is quoted. Lines with less reliable equivalent widths are entered with half weight. Apart from Fe, solar abundances are from Anders and Grevesse (1989); for Fe we adopt the revised value of 7.51 (Holweger et al. 1995).

Obviously the surface composition of β Pic is indistinguishable from that of the Sun. Recently, Lanz et al. (1995) have shown that the low-resolution UV spectrum of β Pic can be reproduced by a metal-*deficient* model with *high* microturbulence (12 ${\rm km\,s^{-1}}$), but the combination of solar metallicity and $\xi = 4\ {\rm km\,s^{-1}}$ works equally well.

Lanz et al. argue that their *HST* GHRS high-resolution spectra rule out the high ξ value. They conclude: 'we can match the UV spectrum of β Pic with a solar composition model at $T_{\rm eff} = 8200$ K'. Other combinations of metallicity and microturbulence – or individual abundances of diagnostic elements – are not considered. We note that their result is fully compatible with our element-by-element analysis.

Table 1. Lines used for abundance determination. Less certain equivalent widths are quoted in italics. M denotes the multiplet number.

El.	M	λ (Å)	χ (eV)	$\log gf$	$\log N_{\rm el}$	W_λ (mÅ)
C I	6	4771.74	7.49	-1.866	8.736	80.7
C I	13	4932.05	7.69	-1.658	8.324	47.4
C I	4	5041.48	7.95	-1.561	8.631	71.2
C I	12	5052.17	7.69	-1.304	8.726	135.9
C I	11	5380.34	7.69	-1.615	8.632	81.2
C I	26	7113.18	8.65	-0.774	8.436	*76.8*
Ti II	20	4287.87	1.08	-1.820	4.500	*36.5*
Ti II	41	4290.22	1.16	-0.930	4.914	164.8
Ti II	41	4300.05	1.18	-0.490	4.270	*142.8*
Ti II	41	4301.91	1.16	-1.200	4.880	*133.6*
Ti II	40	4464.45	1.16	-1.810	4.291	*22.7*
Ti II	31	4468.51	1.13	-0.600	4.431	155.8
Ti II	18	4469.14	1.08	-2.510	5.543	*68.7*
Ti II	50	4563.76	1.22	-0.790	4.419	127.4
Ti II	82	4571.97	1.57	-0.230	4.810	199.9
Ti II	50	4589.96	1.24	-1.620	5.098	*108.2*
Ti II	92	4805.09	2.06	-0.960	5.041	110.4
Ti II	114	4911.19	3.12	-0.650	4.734	*36.4*
Cr II	31	4284.19	3.85	-1.670	5.382	*30.3*
Cr II	39	4565.74	4.04	-1.820	5.380	*17.8*
Cr II	44	4588.20	4.07	-0.627	5.834	160.7
Cr II	44	4592.05	4.07	-1.221	5.933	109.6
Cr II	44	4616.63	4.07	-1.361	5.872	88.0
Cr II	44	4618.80	4.07	-0.840	5.553	109.8
Cr II	44	4634.07	4.07	-0.990	5.801	*120.6*
Cr II	30	4812.34	3.86	-1.960	5.773	*37.8*
Cr II	30	4824.13	3.87	-0.970	5.431	99.0
Fe II	27	4173.46	2.58	-2.513	7.924	*205.1*
Fe II	28	4178.86	2.58	-2.785	7.847	*175.0*
Fe II	27	4233.17	2.58	-1.836	7.399	*220.9*
Fe II	38	4549.47	2.83	-1.957	7.262	188.6
Fe II	37	4555.89	2.83	-2.325	7.484	*174.6*
Fe II	38	4620.52	2.83	-3.079	7.237	*70.5*
Fe II	37	4629.34	2.81	-2.306	7.463	177.2
Fe II	186	4635.32	5.96	-1.275	7.782	*94.4*
Fe II	43	4656.98	2.89	-3.552	7.712	66.5
Fe II	37	4666.76	2.83	-3.221	8.280	*166.6*
Fe II	42	4923.93	2.89	-1.559	7.619	266.9
Fe II	42	5169.03	2.89	-1.303	7.913	*347.1*
Fe II	74	6456.38	3.90	-2.075	8.036	*195.0*
Sr II	1	4077.71	0.00	-0.167	3.163	270.4
Sr II	1	4215.52	0.00	-0.145	2.895	230.2
Ba II	1	4554.03	0.00	0.170	1.708	*103.8*
Ba II	1	4934.08	0.00	-0.150	2.330	177.7
Ba II	2	6141.71	0.70	-0.076	2.356	130.8

5. Discussion

Obviously *the surface composition of β Pic is solar* within a factor two or less. This is true for diffusion indicators like C, Ca, Sr, and Ba, as well as for the metallicity indicators Ti, Cr, and Fe known to respond sensitively to accretion of CS matter in other late A stars of the λ Boo class. In fact, β Pic appears 'outstandingly normal' compared to other ordinary A-type stars where mild abundance anomalies are common. This deserves some comments.

Is β Pic a λ Boo star? We do not confirm the metal deficiency inferred by Paresce (1991) from Geneva photometry, a result that has prompted King and Patten (1992) to suggest that β Pic is a λ Boo star. We note that the *HST* GHRS data analyzed by Lanz and Hubeny (1995) also rule out a low metallicity, and that their own evaluation of Geneva indices leads to a normal rather than subsolar iron abundance.

Why does the signature of accretion not show up in the surface composition of β Pic? Accretion of gas depleted in refractory elements is thought to be responsible for the deficiency pattern of λ Boo stars, and direct evidence for the presence of CS matter is accumulating (e.g. Stürenburg 1993; HRH95; Hauck et al. 1995; Grady et al. 1996). In view of this the absence of surface anomalies in a star like β Pic—with its spectacular disk of gas and dust—is puzzling. A possible explanation is that accretion does not occur at all, or at a rate which is too small to compete with meridional mixing. On the basis of numerical calculations Turcotte and Charbonneau (1993) conclude that 'for stars with equatorial velocities of 125 km s^{-1} or less, and accreting at a rate of $10^{-13} M_\odot$ yr^{-1}, rotationally induced meridional circulation has no significant influence on the evolution of surface abundances, during the accretion episode itself.' The true equatorial velocity of β Pic is probably close to the observed $v \sin i$ value of 132 km s^{-1}, hence the 'observed' thorough mixing implies an accretion rate well below $10^{-13} M_\odot$ yr^{-1}.

Furthermore, a normal surface composition is in contrast to the *AmFm-like abundance anomalies* traceable in other reputedly normal A stars (Holweger and Stürenburg 1993; Hill 1995). Among the stars studied β Pic has the largest $v \sin i$, hence *meridional mixing* appears attractive as an explanation for the inefficient element separation in this star. A closer look at the results of Turcotte and Charbonneau (1993) shows that at 125 km s^{-1} the chemical separation of Ti indeed is effectively shut off a few Myr after the termination of accretion, but Ca remains anomalous for a much longer time. Details depend critically on the radiative forces near the base of the convection zone, hence convective overshoot—neglected in these mixing-length models—may have profound effects. Freytag et al. (1996) have investigated overshoot in a non-rotating model; predicted anomalies of Ca and Ti become much smaller (and may even reverse sign). Therefore we expect that the combined effect of *overshoot and rotation* can explain why the envelope of β Pic is so well mixed.

Finally, *evaporating comet-like bodies*, invoked to explain the variable redshifted absorption features in the spectrum of β Pic (e.g., Lagrange-Henri et al. 1992), may contaminate the stellar surface with matter of non-solar metallicity. A recent estimate (Beust et al. 1996) of the inward mass flux is $\approx 2 \cdot 10^{-9} M_\oplus$ yr^{-1}, or $6 \cdot 10^{-15} M_\odot$ yr^{-1}. According to the previous considerations this is unlikely to cause detectable anomalies.

6. Concluding remarks

Although β Pic as well as the λ Boo stars are cool A-type stars with direct or indirect evidence for the presence of CS matter, β Pic lacks the specific chemical surface anomalies attributed to accretion of gas deficient in refractory elements. In this respect β Pic is not unique. Two other cool A stars with dust disks—π Ara and α PsA—have been studied by HRH95. In both cases the calcium abundance turned out to be approximately solar.

Solar surface composition is not the only property that distinguishes β Pic from λ Boo stars. Within the error limits of about ± 0.1 dex the *surface gravity* of β Pic is that expected for zero-age main-sequence stars of 1.7 to 1.8. $M_\odot$ (Lanz et al. 1995; HRH95). Interestingly, the same is true for π Ara and α PsA (cf. Table 3 of HRH95). By contrast, the gravity of λ Boo stars is generally significantly lower, consistent with their interpretation as pre-main-sequence objects in the final stage of contraction.

In view of this we may expect the disks around β Pic and its dusty analogs to be older than those of λ Boo stars, and possibly more evolved in the sense that less matter is available for accretion. We note that the density distribution of the inner part of the β Pic disk is known to be peculiar. Infrared imaging with 0.3 arcsec resolution indicates depletion of dust in the innermost 40 AU that may be associated with planetary formation (Lagage and Pantin 1994). Recent *HST* images reveal that the inner disk is warped, which is taken as evidence for gravitational perturbation by planets.

A-type stars deserve further study since they provide an excellent opportunity to investigate the connection between surface abundances, the presence of CS matter, and pre-main-sequence evolution.

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