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An abundance analysis of the single-lined spectroscopic binaries with barium stars-like orbital elements

I. Analysis and results

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Abstract. Detailed abundance analyses have been carried out for 17 single-lined binaries (giants and dwarfs) with orbital elements and mass functions similar to those of barium stars, using high-dispersion CCD spectra and model atmospheres. All these binary systems contain an unseen low-mass component, presumably, a white dwarf. A mild enhancement ($+0.1-0.25$ dex) of the averaged s-process elements abundances has been found only for two stars. The heavy-element overabundances in these stars are much less marked than those of the classical barium stars having similar orbital periods. We have concluded that the existence of a white dwarf (WD) companion in binary systems with barium star like characteristics is not sufficient to produce a strong barium star. However, five of the analyzed giants show a significant enhancement ($0.2-0.3$ dex) of barium. The analysis indicates that a main sequence companion has not a significant influence (due to tidal mixing, as has been sometimes suggested) on the internal structure (chemical composition) of the primary star. Since barium enhanced giants occupy a place on the (eccentricity-orbital period) plane similar to BaII stars we have concluded that a mild barium enhancement in these stars is due to mass transfer from the companion during its late phases of evolution. Thus it seems likely that all giants (primaries) in barium star like binary systems with WD component have chemical peculiarities (very slight in some cases) depending, apparently, on the efficiency of mass transfer in a specific binary system. The significant enhancement of heavy elements in the atmospheres of two radial velocity non-variable barium stars shows then that these barium stars have either very long orbital periods or high inclined orbital planes.

Key words: binaries: spectroscopic — stars: chemically peculiar — stars: abundances — stars: fundamental parameters — stars: evolution

1. Introduction

The binarity of barium stars (McClure et al. 1980; McClure 1983; Jorissen & Mayor 1988; McClure & Woodsworth 1990) and the white dwarf (WD) nature of the companion (Böhm-Vitense 1980; Dominy & Lambert 1983; Böhm-Vitense et al. 1984) indicates that a transfer of heavy element rich matter from the AGB companion (now WD) towards the barium stars is a good explanation for the chemical peculiarities of the latter. Therefore, the binarity appears to be a necessary condition for producing barium stars (Jorissen & Boffin 1992). Mass transfer is possible either through Roche lobe overflow (Iben & Tutukov 1985) or wind accretion (Boffin & Jorissen 1988). Wind accretion within the binary system is very likely to be responsible for the contamination of the barium star, as suggested by the correlation between the orbital period and the level of chemical peculiarities (Začs 1994; Boffin & Začs 1994).

On the other hand, a lot of spectroscopic red giant binaries with unseen companion (probably WD in some cases) whose orbits have similar characteristics to those of the barium stars in all probability have solar abundances of the heavy elements (Jorissen & Boffin 1992;

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Boffin et al. 1993). Furthermore they (Boffin & Jorissen 1992) identify three normal giants with directly discovered WD companions (ξ^1 Cet, HD 21120, HD 81817). The existence of binary DR Dra (K0III) which has a long orbital period (904 days) and hot WD companion discovered by Fekel & Simon (1985) and Fekel et al. (1993) lead to the conclusion that the existence of WD companion in BaII star like system is not sufficient to produce a barium star. Unfortunately, the problem with chemical peculiarities is complicated, because a part of the barium stars may be chemically mildly peculiar and, therefore, an enhancement of s-process elements is difficult to detect, especially, on the base of a spectrum in a narrow spectral region. For example, Pilachowski (1977) and Začs (1994) suggested that ξ^1 Cet (HD 13611) has a mild s-process enhancement.

An important step towards a better understanding of the phenomenon of barium stars is a detailed abundance analysis of spectroscopic binaries with BaII stars like orbital elements, especially, binaries with directly observed WD companions. The purpose of this study is to obtain a well represented abundance pattern for a large sample of long-period spectroscopic binaries to compare these abundances with solar ones and to analyze possibly the influence of the unseen companion on the atmosphere of the primary star to understand better the sufficient conditions for the formation of abundance peculiarities. Since the observational material is very extensive, we give here only the analyses and results. The equivalent widths and individual abundances will be published in a companion paper, in the Supplement Series.

2. Observations and data reduction

High resolution spectra of the program stars were obtained with the 6 m and 1 m Telescopes of the Special Astrophysical Observatory during 1993-94. The Nasmyth echelle spectrometer LYNX (Panchuk et al. 1993) and coude-echelle spectrometer CEGS (Musaev 1993, 1996) equipped with the 580×530 pixels CCD detector were used. The LYNX service observations were carried out by the 6-m telescope staff Drs. G. Galazutdinov, V.G. Klochkova, and V.E. Panchuk in the time intervals allocated to L. Začs by the 6-m Telescope Programmes Committee. The program stars were selected with the aim to define a sample of binary systems with orbital parameters similar to those of barium stars but for a range of orbital periods (P), mass function ($f(M)$), and eccentricity (e) values to provide an optimal condition to analyze the sufficient conditions for the formation of the chemical peculiarities. Some binary systems with F-G dwarfs as primaries were included in the observation program since it is supposed that mass transfer can occur also to the main sequence star. In addition two mild (Ba 1.0) BaII stars with a constant radial velocity (RV) were selected (Jorissen 1994) to check the enhancement of the heavy elements. ϵ Vir (G8IIIab) was chosen as a primary comparison standard of chemical composition and Procyon (F5IV-V) was used as a secondary standard to establish the properties of dwarfs. About thirty single line spectroscopic binaries were selected for this program mainly from the eighth catalogue of Batten et al. (1989). Table 1 gives the physical data for 19 stars and two standards discussed in this work. The spectral classification were taken from Hoffleit (1982) and Yamashita & Norimoto (1981). Apparent magnitudes are from Hoffleit (1982). The sixth column indicates the telescope used for observations. The orbital elements of spectroscopic binaries were taken from Batten et al. (1989).

The LYNX spectra covered the spectral region $5000 - 7200$ Å in 30 wavelength bands (overlapping in regions from 5000 to 5200 Å). Each region spanned from 50 to 80 Å and had a signal-to-noise ratio in the range of $70 - 150$. The resolution, as measured from the FWHM of lines from a thorium lamp, was 30 000 ($\sim$ 0.2 Å at 5500 Å). The CEGS spectra covered the spectral region from 4400 Å to 6900 Å. The 39 wavelength regions were observed at a resolution of $0.15 - 0.2$ Å depending on the wavelength. Each region spanned $50 - 60$ Å. Most of these spectra have a S/N more than 100. LYNX and CEGS wavelengths regions in the red ($\lambda > 5000$ Å) spectral region are similar.

The raw spectra were reduced for CCD dark current, echelle-grating scattered light, cosmic particle events, divided by flat-fields and wavelength calibrated using standard DECH routines realized in SAO on IBM PC (Galazutdinov 1992). The continuum of the red giant spectrum was defined by a number of narrow spectral regions, selected to be relatively free of lines. The sample of spectra from the program stars are shown in Figs. 1 and 2 along with those of standards ϵ Vir and Procyon. Figures 1 and 2 show spectra near the BaII lines 6141.72 Å and 6496.90 Å used for the determination of Ba abundance. The 6587 Å CI line region is illustrated in Fig. 3. The lines for the abundance analysis were chosen to be as free as possible of blends. Lines showing no significant line asymmetry were measured by interactively fitting Gaussian functions to the line profiles. The number of lines measured per star was typically $500 - 700$, however, as a rule the lines stronger than 200 mÅ were not used in the analyses. The internal accuracy of the equivalent widths is of order 5% based on comparison of values obtained from overlapping spectra. The list of lines used in the abundance analysis and measured equivalent widths for each star will be published separately. The external accuracy of the equivalent widths can be assessed by comparing our results with independent measurements of common stars by other authors. Equivalent widths for a few of the program stars are available from the published analyses. In Figs. 4a and b a comparison for standard stars is shown. As can be seen the equivalent widths scales are in general consistent.

Table 1. Physical data and observations mode for the program stars. Last three columns indicate orbital period, eccentricity, and mass function, respectively

HD	HR	Name	V	Sp	Obs.	P(days)	e	f(M)
6582	321	μ Cas	5.15	G5Vp	1	8393	0.30	0.017
13530	645	6 Per	5.31	K0III	1	1650	0.75	0.122
21754	1066	5 Tau	4.10	K0II-III	1	960.0	0.40	0.044
61421	2943	Procyon	0.37	F5IV-V+WD	1	40.65y	0.40	1.76&0.65$M_{\odot}^{*}$
76943	3579		3.97	F5V	1	7980.7	0.15	0.051
113226	4932	ϵ Vir	2.83	G8IIIab	1,6			
116594	5053		6.44	K0III+ G-dwarf	6	1366.8	0.19	0.47
119185			8.89	K0III,Ba1.0	6			
120539	5201	6 Boo	4.91	K4III	1	944	0.41	0.00013
121370	5235	η Boo	2.68	G0IV	1	494.2	0.26	0.027
130255			8.86	G4IV,Ba1.0	6			
155410	6388		5.08	K3III	1	876.3	0.61	0.005
160538		DR Dra	6.55	K0III+WD	6	903.8	0.072	0.00351
166478			7.97	K0	6	659.4	0.08	0.015
168532	6860		5.27	K3III,Ba0.4	1	485.5	0.36	0.14
170737			8.08	G8III-IV	6	1284	0.5	0.023
176155	7165	FN Aql	5.38	F8Ib	1	1435	0.01	0.0064
176524	7180		4.82	K0III,Ba0.2^{+}	1	258.5	0.21	0.0054
179558			7.94	G5V	6	2561	0.19	0.024
181602			7.55	F5V	6	208.8	0.37	0.0012
204934			8.7	K1III	6	144.4	0.10	0.003

* Companion masses from Steffen (1985)

\+ Lu (1991)

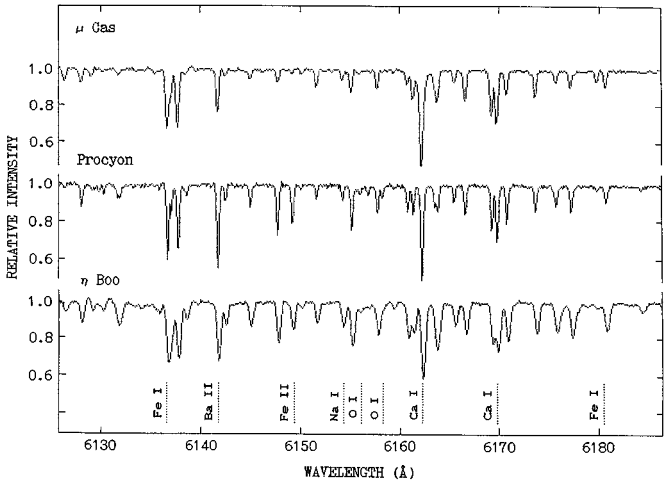

Fig. 1. Sample spectra for μ Cas and η Boo along with the standard Procyon in the wavelength range 6126 – 6185 Å. Measured features include BaII 6141.72 Å, FeII 6149.24 Å, NaI 6154.22 Å, OI 6155.99 Å, 6156.78 Å, 6158.19 Å, CaI 6162.17 Å, and FeI 6180.21 Å

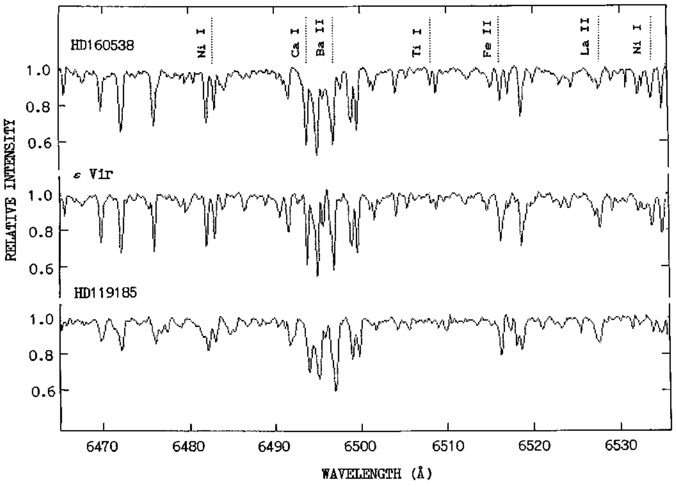

Fig. 2. Sample spectra for HD 160538 and HD 119185 along with the standard ϵ Vir in the wavelength range 6465 – 6535 Å. Measured features include NiI 6482.81 Å, CaI 6493.78 Å, BaII 6496.9 Å, FeII 6516.05 Å, and LaII 6526.95 Å

3. Analysis

We employed the standard LTE line analysis program WIDTH6 of R.L. Kurucz adapted by V. Tsymbal for using on IBM PC. Atmospheric models for G-K giants were interpolated within the grid of models given by Bell et al. (1976) and by Kurucz (1979) for dwarfs. For some high luminosity cool stars additional atmospheric models were computed in 1992 by I. Bikmaev using the MARCS code of Gustafsson et al. (1975). The metallicity nearest to the derived iron group abundance was used to derive the final model used for a program star.

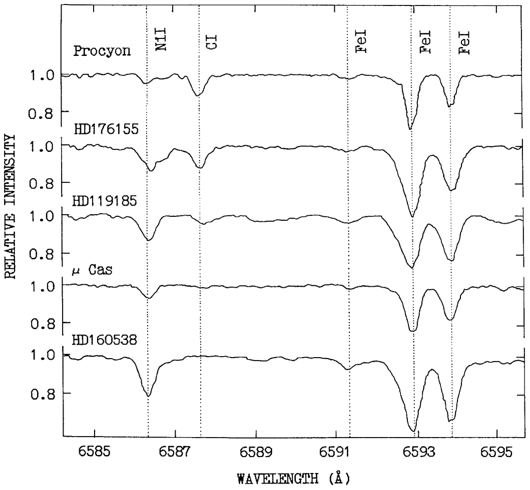

Fig. 3. The spectra of four program stars along with Procyon near CI 6587.62 Å. Measured features include NiI 6586.31 Å, CI 6587.62 Å, FeI 6591.31 Å, FeI 6592.92 Å, and FeI 6593.88 Å

The theoretical equivalent width of each line is computed assuming at start the solar abundance, and the abundance is modified iteratively until the equivalent width matches the observed one. We determined a giant's abundances relative to normal G8 giant ϵ Vir and a dwarf's abundances relative to Procyon (F5IV-V). For differential abundances the standard notation $[X]=[X/H]=\frac{1}{m}\sum_{i=1}^{m}\log\epsilon_i^*(x)-\log\epsilon_i^{\rm st}(x)$ is used. There $\log\epsilon(x)=\frac{n(x)}{n(H)}$, $n(x)$ is the number density of an element x, and m = the number of lines used. Because the goal of this study was to identify also mild barium stars, which possess small s-process overabundances, accurate abundances were required, therefore, a particular care was taken to ensure a consistency in the determination of the atmospheric parameters and abundances. Since the analysis is a differential one, and abundances are measured relative to those of a similar star, the effects of systematic errors in the height of the continuum, possible line blanketing effects in red giants, uncertainties in quantities of the oscillator strengths, and non-LTE effects are lessened. In order to improve the accuracy of adopted atmospheric parameters, excitation temperature, spectroscopic gravity, and microturbulent velocity were derived using differential abundances of each line relative to the corresponding line in the standard star instead of absolute abundances for all iron group elements. We have found that this improvement led to a high degree of internal consistency in the analysis. Therefore, we expect that a large number of lines for stars, great homogeneity of data, and the improvements of the analysis will ensure a high internal accuracy of the atmospheric parameters and chemical composition.

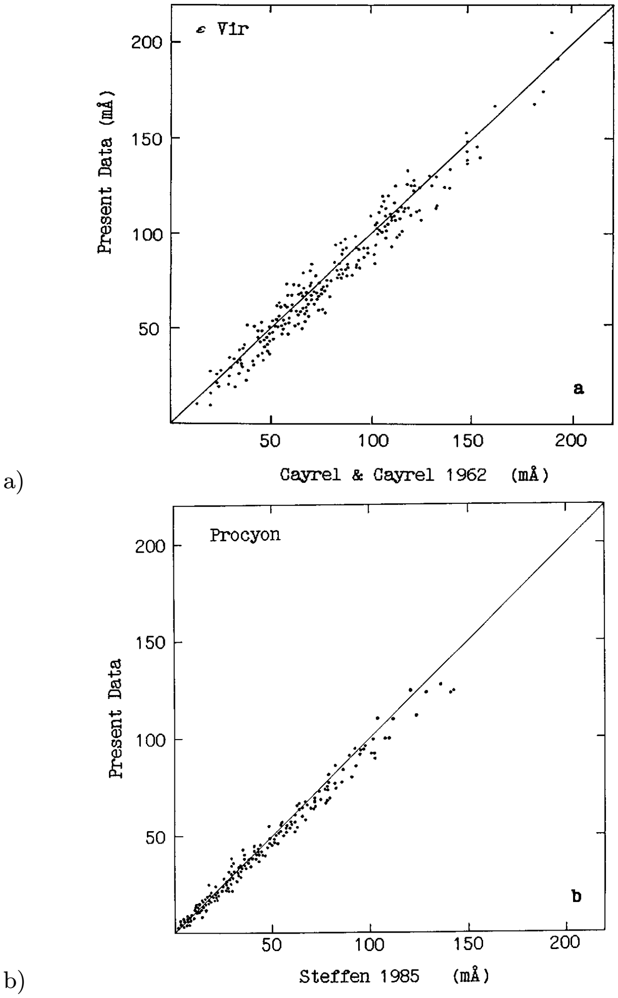

Fig. 4. a) and **b)** The comparison of equivalent-widths between this paper and others for standard stars: **a)** ϵ Vir, **b)** Procyon

The atomic oscillator strengths were taken from Luck & Bond (1985), Thevenin (1989, 1990), and Gurtovenko & Kostyk (1989) and will be given separately together with the measured equivalent widths. Since the analysis is done differentially with respect to a standard, accurate oscillator strengths are not so critical.

Table 2. The colours, effective temperatures derived from the colour indices, excitation temperatures, and the final adopted atmospheric parameters for all program stars. The last column indicate the averaged abundances of s-process elements scaled to the metallicities

HD	B-V	R-I	T_{eff} (B-V)	T_{eff} (R-I)	ex	T_{eff}	logg	ξ_t	[A]	[s/XII]
6582	0.70	0.43	5364		5250	5250	4.5	1.2	-1.0	-0.14
13530	0.93				4800	4800	2.5	1.5	-0.5	-0.07
21754	1.13	0.54		4795	4850	4850	2.5	2.2	0.0	+0.12
61421	0.42	0.23	6563		6500	6500	4.0	2.1	0.0	
76943	0.43	0.22	6528		6630	6630	4.0	2.8	0.0	-0.02
113226	0.94	0.45		5187	5130	5130	3.0	2.0	0.0	
116594	1.06				4800	4800	2.5	2.0	0.0	-0.09
119185	1.066	0.509		4921	4950	4950	2.6	1.8	-0.5	+0.22
120539	1.43	0.74		4199	4250	4250	1.7	2.0	0.0	+0.01
121370	0.58	0.29	5997		6000	6000	3.7	2.2	0.0	-0.18
130255	1.167	0.593		4601	5000:	5000	3.0	2.0	-0.5	+0.50
155410	1.28	0.64		4450	4420	4420	2.0	2.0	0.0	-0.08
160538	1.05				4800	4800	2.5	2.0	0.0	-0.03
166478					4800	4800	2.5	2.0	0.0	-0.09
168532	1.49	0.75		4179	4270	4270	1.2	2.3	0.0	+0.06
170737				5003	5000	5000	3.0	1.3	-0.5	-0.02
176155	0.67	0.43			6000	6000	1.4	4.5	0.0	+0.25
176524	1.15	0.56		4719	4650	4650	2.0	2.0	0.0	+0.05
179558	0.76		5360		5500	5500	4.3	2.0	0.0	+0.07
181602					6350	6350	3.9	2.0	0.0	+0.02
204934					4950	4950	2.8	1.9	0.0	-0.13

Effective temperatures, T_{eff}, were estimated from the colors using the calibration by Bell & Gustafsson (1989) for giants and calibration by Bikmaev (1992) for dwarfs. Photometric colors were taken from the literature. We used the $(R-I)$ broad-band Johnson system colors taken from the Yale Bright Star Catalogue (Hoffleit 1982) for giants. These near-infrared colors are unaffected by the possible violet opacity in peculiar red giant stars. $(B-V)$ colors were used for most dwarfs. We used the line excitation equilibrium for the iron group metal lines as an additional check for temperature determination. To cancel the possible non-LTE effects, especially for lines of low excitation potential, we used the differential abundance relative to the standard. The relation between differential abundances for lines of the iron group elements and excitation potential is illustrated in Fig. 5 for two giants and one dwarf. As can be seen a large number of lines and a small scatter ensured the low internal errors for our excitation temperatures and reflect a good quality for the data. We compared (Table 2) our spectroscopic temperatures (T_{ex}) with those that can be deduced from colors $(R-I)$ or $(B-V)$. The agreement between spectroscopic and photometric temperatures is good for all of the program stars, excluding HD 130255, for which the excitation temperature is much higher (+400 K) than the color temperature. In this case we adopted the excitation temperature also for T_{eff} because it is more consistent with the spectral class. On the whole, the effective temperatures can be determined to $\pm 100-150$ K.

Gravities $\log g$, were derived requiring both ionized and neutral iron group element lines to yield the same abundance. It should be kept in mind that spectroscopic gravities may be affected by departures from LTE when we use XI/XII ionization equilibrium for the determination, therefore, we used the differential abundance relative to the standard again. The error in $\log g$ as determined from iron group lines is approximately ± 0.3, when g is measured in cm s^{-2}.

We have derived microturbulent velocities, ξ_{t}, in the conventional way of adjusting ξ_{t}, to eliminate any trend of elemental abundance with equivalent width. The differential elemental abundances relative to standard, derived from individual lines of iron group elements, were computed for a range of ξ_{t} values. Plots of abundance as a

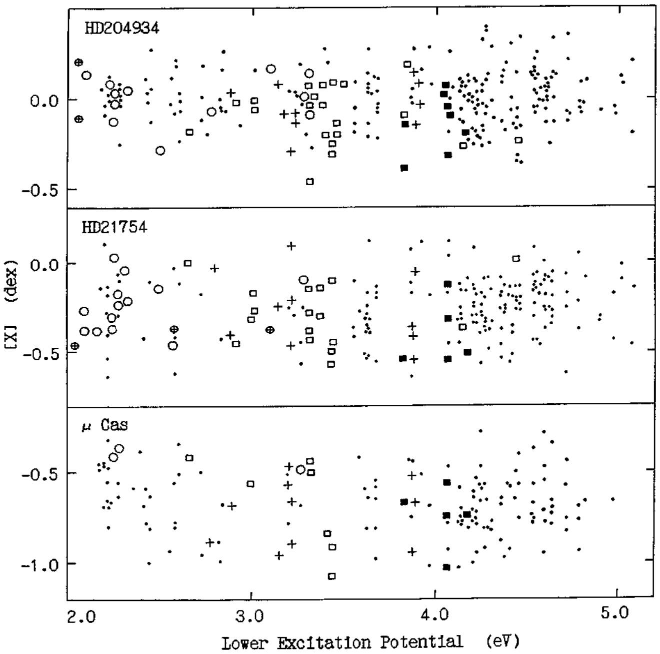

Fig. 5. The differential abundances of FeI (●), FeII (+), TiI (○), TiII (⊕), CrI (□), and CrII (■) versus excitation potential relation for three program stars illustrating the estimation of the spectroscopic temperatures

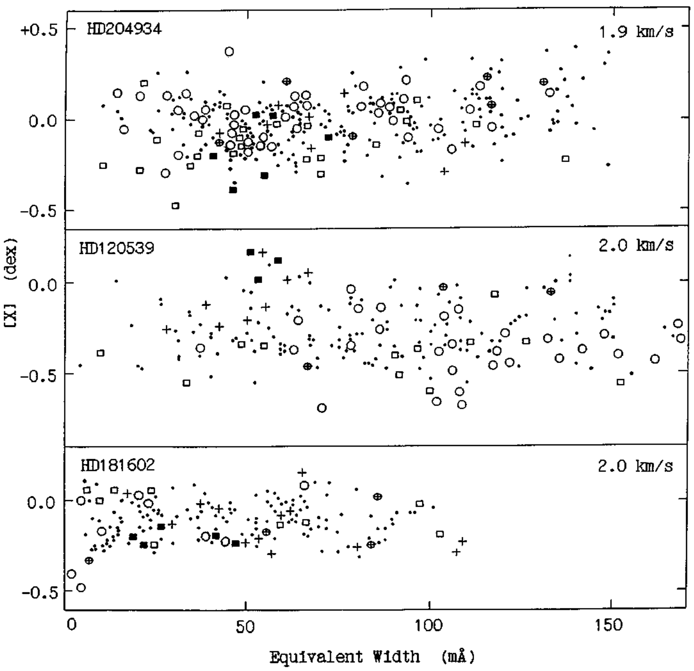

Fig. 6. The differential abundance versus equivalent width relation for three program stars illustrating the estimation of the microturbulent velocity. Signs indicate: (●) FeI, (+) FeII, (○) TiI, (⊕) TiII, (□) CrI, (■) CrII

function of equivalent width for all choices of microturbulence, showed where the dependence vanished. Typical examples illustrating the ξ_t determination for three stars are illustrated in Fig. 6. The microturbulent velocities can be determined to ±0.3 km s^{-1}.

The analysis of uncertainties in the derived abundances due to errors in the model parameters shows that a combination of uncertainties in effective temperature of 150 K, of 0.3 in surface gravity, and of 0.3 km s^{-1} in microtrubulent velocity would lead to errors no more than 0.2 dex in the derived abundances for most elements. Since we used existing models for metal abundances closest (±0.25 dex) to those of the real metallicities there could be errors due to the model's approximation. We examined errors in the derived abundances due to uncertainties in model metal abundance $[A]$ of ±0.25 dex. We concluded that these uncertainties lead to errors in the abundance for most elements no more than 0.1 dex. Since we used the abundances of s-process elements (barium) normalized to the metallicities (XII) the influence of the model's approximation to the final results is even less (< 0.05 dex). The independence of wavelength of the differential chemical abundances estimated from different lines of neutral iron, illustrated in Fig. 7 for three program stars, shows that we correctly defined the continuum.

4. Results and discussion

4.1. The comparison stars

The chemical analyses of the program stars were carried out relative to the comparison stars ϵ Vir (G8IIIab) and Procyon (F5IV-V). ϵ Vir was chosen as a primary comparison standard, because the chemical composition of this star has been analyzed in detail relative to the Sun (see, for example, Cayrel & Cayrel 1963; Tomkin & Lambert 1986). The atmospheric composition of ϵ Vir corresponds to the solar one within the probable error of determination and no systematic enrichment in heavy-element abundance can be detected. We adopted the following atmospheric parameters ($T_{\rm eff}$, $\log g$, ξ_t), and model metal abundance $[A]$ for ϵ Vir: 5130 K, 3.0, 2.0 km s^{-1}, 0.0. These parameters agree in general with those obtained by Tomkin & Lambert (1986) and McWilliam (1990). For Procyon, we have adopted $T_{\rm eff} = 6500$ K, $\log g = 4.0$, $\xi_t = 2.1$ km s^{-1}, which is the best value according to the compilation of Steffen (1985).

4.2. Stellar parameters

The final adopted atmospheric parameters (effective temperature, surface gravity, microturbulence velocity) and model metal abundances for the program stars are listed in Table 2. Some of the stars have previously published parameter determinations. We compared our results with

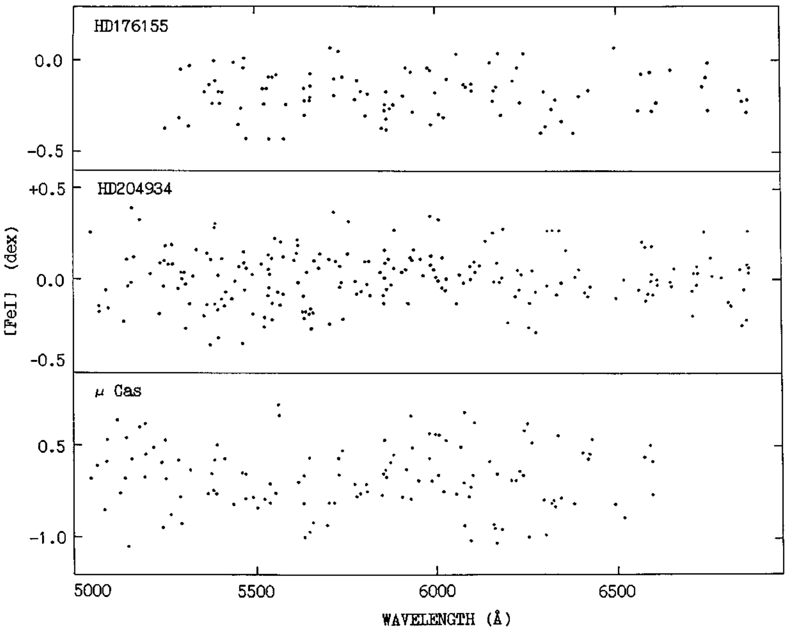

Fig. 7. The differential abundance of iron [FeI] versus wavelength relation for three program stars illustrating a correctly defined continuum

those obtained by Edvardsson et al. (1993) for η Boo, and by McWilliam (1990) for 6 Per, 5 Tau, 6 Boo, η Boo, HR 6388, HR 6868, and HR 7180. We obtained an excellent agreement between our results and results obtained by Edvardsson et al. (1993) for η Boo, 6068 K, $\log g = 3.83$, 2.0 km s^{-1}. The comparison between our results and those of McWilliam (1990) shows a good agreement for temperature ($\Delta T_{\rm eff} \leq \pm150$ K for 16 Per, 5 Tau, η Boo, HR 6388, HR 6860, HR 7180), for gravity ($\Delta \log g \leq \pm0.3$ km s^{-1} for 5 Tau, 6 Boo, η Boo), and for microturbulent velocity ($\Delta\xi_{\rm t} \leq \pm0.3$ km s^{-1} for 5 Tau, 6 Boo, HR 6388, HR 6860, HR 7180). But for some stars there are disagreements between our results and those obtained by McWilliam (1990) for gravity (6 Per, HD 168532, HR 7180), turbulent velocity (6 Per), and effective temperature (6 Boo). Our gravity values for these three stars are lower than those derived by McWilliam (1990), who estimated gravity using the relation between temperature, mass, luminosity, and gravity.

We checked our spectroscopic gravities for dwarfs with those derived using temperature-mass-luminosity relation and good trigonometric parallaxes ($0\farcs134$ for μ Cas, $0\farcs066$ for HR 3579, $0\farcs091$ for η Boo). There is an excellent agreement for μ Cas, but for HR 3579 and η Boo spectroscopic gravities are somewhat lower than those obtained from parallaxes. The atmospheric parameters of binaries are found to be typical of single main-sequence or giant stars, respectively.

4.3. The relative abundances

The mean differential abundances of the light and iron group elements (Na, Mg, Si, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu), obtained using neutral or ionized lines, and the mean abundances of the s-process elements (Y, Zr, Ba, La, Ce, Nd) for all program stars are given in Table 3, along with the standard deviations of averaged abundances estimated from individual lines, and the number of lines used in the analysis. In Table 4 the mean abundances of separate elements for all stars are given. In the literature there are previous abundance determinations available for some of the stars. We have found a generally good agreement (Fig. 8) for the light and iron-peak elements, as well as for barium when we compare our results for η Boo to the results of Edvardsson et al. (1993). In the following we shall comment on some details of the abundance distributions.

4.3.1. Carbon and oxygen

Carbon abundances have been derived for 11 of the program stars using the neutral carbon line at λ5380.31 or at λ6587.62 Å. Carbon appears to be enhanced only for HR 6860 and, possibly, slightly for HR 7180. We have found no indication of carbon processing from any other program star. The oxygen abundance has been derived only for 7 stars using the forbidden oxygen line at λ6300.31 Å. The analysis shows that oxygen may be slightly ($\sim$ 0.2 dex) overabundant in the atmospheres of six stars.

Table 3. The averaged differential abundances of light and iron group elements, obtained from neutral (XI) and ionized (XII) lines, and of s-process elements for the program stars along with the standard deviation, and the number of lines. The last column indicate the Ba abundance scaled to the metallicity

HD	[XI]±σ(n)	[XII]±σ(n)	[s]±σ(n)	[Ba/XII]
6582	−0.64±0.22(262)	−0.66±0.21(28)	−0.80±0.23(10)	−0.25
13530	−0.55±0.21(380)	−0.51±0.15(29)	−0.58±0.18(33)	−0.10
21754	−0.07±0.12(279)	−0.02±0.15(19)	+0.09±0.20(18)	+0.26
76943	+0.16±0.18(209)	−0.08±0.17(30)	−0.10±0.16 (7)	−0.13
116594	−0.15±0.17(249)	−0.11±0.18(16)	−0.20±0.16(16)	−0.06
119185	−0.49±0.22(205)	−0.56±0.20(26)	−0.34±0.22(20)	+0.42
120539	−0.25±0.17(283)	−0.10±0.18(24)	−0.15±0.32(24)	+0.07
121370	+0.31±0.14(261)	+0.19±0.11(36)	+0.01±0.19(17)	−0.16
130255	−0.69±0.30(207)	−0.67±0.35(24)	−0.17±0.17(15)	+0.53
155410	−0.22±0.15(269)	−0.18±0.19(27)	−0.26±0.23(23)	−0.11
160538	−0.22±0.19(372)	−0.27±0.21(35)	−0.28±0.19(30)	+0.25
166478	−0.20±0.18(225)	−0.17±0.07(12)	−0.26±0.23(11)	+0.23
168532	−0.20±0.17(310)	−0.20±0.18(25)	−0.14±0.24(33)	+0.27
170737	−0.83±0.21(351)	−0.85±0.27(36)	−0.87±0.26(22)	−0.13
176155	−0.18±0.18(188)	−0.27±0.21(27)	−0.03±0.36(23)	+0.51
176524	−0.18±0.14(286)	−0.21±0.17(27)	−0.16±0.19(24)	+0.18
179558	+0.03±0.18(254)	−0.08±0.22(32)	−0.20±0.21 (8)	−0.11
181602	−0.11±0.11(224)	−0.14±0.11(33)	−0.12±0.16(14)	+0.06
204934	+0.01±0.15(407)	−0.04±0.16(37)	−0.17±0.16(32)	−0.16

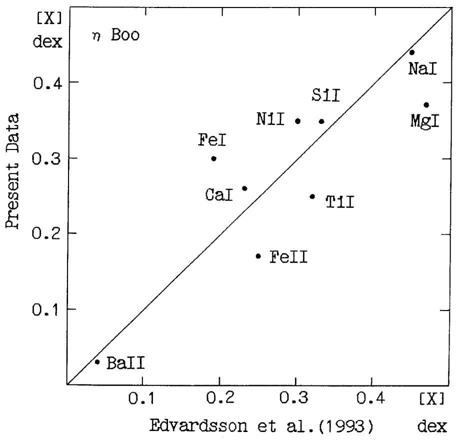

Fig. 8. The comparison of abundance determinations of this paper and others for η Boo

4.3.2. Na to Si and iron group elements

No significant deviations from the solar abundance pattern can be found among these elements. The mean abundance for 17 single lined binaries relative to the standards is $[X/\mathrm{Fe}] \cong 0.0$ with typical standard deviation $0.10 - 0.15$ dex. Only the abundance of Mn shows a larger dispersion from star to star in the sample: $[\mathrm{Mn/Fe}] = -0.05 \pm 0.20$ dex.

4.3.3. Heavy elements (Y to Eu)

The seven elements heavier than iron are traditionally identified with synthesis by the neutron capture s-process. The main sample of spectroscopic binaries includes seventeen stars (μ Cas, 6 Per, 5 Tau, HR 3579, HR 5053, 6 Boo, η Boo, HR 6388, DR Dra, HD 166478, HR 6860, HD 170737, FN Aql, HR 7180, HD 179558, HD 181602, HD 204934). Detailed differential abundance analysis relative to the standard stars shows that no one from these barium star like binaries have a significant enhancement ($[\mathrm{s/XII}] > 0.25$ dex) of averaged s-process elements scaled to iron group elements (see Tables 2 and 3). Taken together the mean abundance of these elements is solar. Only giant 5 Tau (K0II-III, $P = 960$ days) and supergiant FN Aql (F8Ib, $P = 1435$ days) show a mild enhancement ($0.1 - 0.25$ dex) of s-process elements, however, overabundance of heavy elements in these stars are small, different from those of certain BaII stars with similar orbital periods (Začs 1994). Although direct evidence for WD companion has been confirmed only in the

Table 4. The mean differential abundances $[X]$ of separate elements for all program stars, along with the standard deviation of abundances estimated from individual lines, and the number of lines used in the analysis

Element	HD 6582	HD 13530	HD 21754
C I	-0.83 (1)	-	-0.08 (1)
O I	-	-0.40 (1)	+0.15 (1)
Na I	-0.76±0.08 (3)	-0.32±0.12 (2)	-0.13±0.05 (2)
Mg I	-0.34±0.15 (4)	-0.31±0.21 (4)	-0.14±0.17 (4)
Si I	-0.51±0.09 (20)	-0.33±0.10 (10)	0.00±0.08 (10)
Ca I	-0.54±0.15 (17)	-0.37±0.17 (14)	-0.09±0.14 (13)
Sc I	-	-0.63 (1)	+0.14 (1)
Sc II	-0.63±0.15 (8)	-0.46±0.13 (9)	-0.05±0.18 (7)
Ti I	-0.42±0.16 (11)	-0.42±0.14 (44)	-0.07±0.08 (31)
Ti II	-0.35±0.22 (3)	-0.37±0.13 (6)	-0.03±0.18 (2)
V I	-0.78±0.21 (9)	-0.59±0.12 (17)	-0.07±0.11 (18)
V II	-0.55 (1)	-	+0.13 (1)
Cr I	-0.69±0.23 (12)	-0.60±0.46 (22)	-0.05±0.11 (13)
Cr II	-0.76±0.16 (5)	-0.62±0.12 (4)	-0.05±0.03 (2)
Mn I	-0.85±0.13 (9)	-0.82±0.26 (10)	-0.13±0.10 (9)
Fe I	-0.68±0.17(129)	-0.59±0.16(170)	-0.05±0.12(141)
Fe II	-0.75±0.17 (11)	-0.59±0.11 (10)	-0.01±0.11 (7)
Co I	-0.71±0.14 (5)	-0.42±0.10 (10)	+0.01±0.06 (7)
Ni I	-0.66±0.14 (38)	-0.56±0.15 (38)	-0.12±0.14 (29)
Cu I	-0.53±0.14 (2)	-0.60±0.22 (2)	-0.38 (1)
Y I	-0.91 (1)	-0.41 (1)	+0.18 (1)
Y II	-0.82±0.23 (4)	-0.65±0.16 (7)	-0.01 (1)
Zr I	-	-0.73±0.16 (3)	-0.21±0.13 (4)
Zr II	-	-0.79±0.02 (2)	-
Ba II	-0.91±0.12 (3)	-0.61±0.13 (3)	+0.24±0.08 (3)
La II	-	-0.73±0.13 (4)	+0.07±0.06 (5)
Ce II	-	-0.55±0.03 (3)	+0.30 (1)
Pr II	-	-0.47±0.07 (2)	-
Nd II	-0.54±0.21 (2)	-0.39±0.12 (8)	+0.28±0.09 (3)

Element	HD 76943	HD 116594	HD 119185
C I	+0.01 (1)	-	-
Na I	-0.02±0.05 (3)	-0.17±0.15 (4)	-0.18±0.26 (3)
Mg I	+0.07±0.27 (2)	-0.07±0.06 (3)	-0.24 (1)
Si I	+0.14±0.17 (14)	0.00±0.18 (11)	-0.50±0.14 (7)
Ca I	+0.34±0.23 (14)	-0.12±0.12 (14)	-0.22±0.17 (9)
Sc II	-0.19±0.07 (6)	-0.03±0.23 (5)	-
Ti I	+0.24±0.16 (10)	-0.15±0.17 (27)	-0.59±0.28 (6)
Ti II	-0.07±0.19 (4)	-0.26±0.09 (2)	-0.58±0.17 (14)
V I	+0.26±0.18 (5)	-0.15±0.16 (19)	-0.53±0.15 (7)
V II	-	-0.17±0.20 (3)	-0.59±0.19 (19)
Cr I	+0.02±0.24 (8)	-0.34±0.14 (7)	-
Cr II	0.00±0.18 (7)	-	-0.26±0.18 (8)
Mn I	+0.26±0.09 (7)	-0.29±0.01 (3)	-0.65±0.13 (6)
Fe I	+0.14±0.15(120)	-0.18±0.16(126)	-0.60±0.14 (6)
Fe II	-0.07±0.16 (13)	-0.10±0.04 (6)	-0.49±0.20(107)
Co I	+0.01±0.27 (3)	-0.01±0.15 (8)	-0.49±0.15 (7)
Ni I	+0.17±0.14 (21)	-0.12±0.17 (26)	-0.48±0.15 (8)
Cu I	+0.13±0.10 (2)	-	-0.59±0.24 (21)
Zn I	-	-	-0.57 (1)
Y I	-	-0.06±0.00 (2)	-0.27±0.04 (2)
Y II	+0.05±0.11 (3)	-0.16±0.02 (2)	-0.45±0.15 (5)
Zr I	-0.17 (1)	-0.41±0.11 (4)	-0.53±0.24 (2)
Zr II	-0.26 (1)	-	-
Ba II	-0.21±0.10 (2)	-0.17±0.08 (3)	-0.14±0.18 (2)
La II	-	-0.07±0.08 (3)	-0.07±0.08 (2)
Pr II	-	-	-0.46 (1)
Nd II	-	-0.15±0.16 (2)	-0.34±0.22 (6)
Eu II	-	-0.04 (1)	-0.35 (1)

Element	HD 120539	HD 121370	HD 130255
C I	-	+0.29±0.04 (2)	-
O I	-0.01 (1)	-	-
Na I	-0.45±0.05 (2)	+0.44±0.03 (2)	-0.51±0.34 (2)
Mg I	-0.35±0.14 (3)	+0.37±0.22 (3)	-0.62 (1)
Si I	-0.12±0.09 (9)	+0.35±0.10 (11)	-0.86±0.15 (6)
Ca I	-0.36±0.17 (14)	+0.26±0.17 (15)	-0.45±0.17 (9)
Sc I	-0.21 (1)	-	-
Sc II	-0.20±0.16 (7)	+0.21±0.08 (9)	-0.59±0.20 (6)
Ti I	-0.35±0.15 (30)	+0.25±0.15 (16)	-0.37±0.23 (24)
Ti II	-0.18±0.20 (3)	+0.18±0.15 (7)	-0.40±0.34 (6)
V I	-0.05±0.14 (16)	+0.24±0.10 (7)	-0.28±0.31 (17)
V II	0.00±0.16 (3)	+0.02 (1)	-0.30 (1)
Cr I	-0.33±0.18 (16)	+0.32±0.06 (13)	-0.73±0.16 (5)
Cr II	+0.10±0.07 (3)	+0.21±0.13 (7)	-0.72±0.29 (4)
Mn I	-0.15±0.19 (9)	+0.59±0.20 (8)	-1.08±0.18 (7)
Fe I	-0.25±0.15(145)	+0.30±0.12(147)	-0.82±0.21(104)
Fe II	-0.09±0.14 (8)	+0.17±0.07 (12)	-0.98±0.20 (7)
Co I	-0.08±0.10 (7)	+0.29±0.13 (3)	-0.61±0.22 (9)
Ni I	-0.23±0.14 (30)	+0.35±0.12 (34)	-0.69±0.17 (21)
Cu I	-0.06 (1)	+0.53±0.02 (2)	-0.92±0.06 (2)
Y I	-0.17±0.22 (3)	-	-
Y II	-0.07±0.21 (4)	0.00±0.24 (6)	-0.08±0.11 (4)
Zr I	-0.65±0.17 (5)	-0.02±0.16 (2)	-0.17±0.04 (2)
Ba II	-0.03±0.03 (3)	+0.03±0.15 (3)	-0.14±0.11 (3)
La II	-0.09±0.18 (4)	+0.15 (1)	-0.19±0.06 (2)
Ce II	-	-0.05±0.16 (2)	-
Pr II	+0.27 (1)	-	-0.59 (1)
Nd II	+0.14±0.05 (4)	+0.03±0.15 (3)	-0.17±0.19 (3)
Eu II	-0.05 (1)	-	-0.58 (1)

Element	HD 155410	HD 160538	HD 166478
C I	-0.21 (1)	-	-
O I	-	-	-0.06 (1)
Na I	-0.20±0.01 (2)	-0.12±0.07 (3)	-0.13±0.21 (4)
Mg I	-0.15±0.11 (3)	-0.09±0.17 (4)	-0.13±0.22 (3)
Si I	-0.03±0.09 (9)	-0.33±0.11 (10)	-0.07±0.17 (8)
Ca I	-0.26±0.11 (10)	+0.15±0.15 (18)	-0.19±0.17 (15)
Sc I	-0.14 (1)	-	-
Sc II	-0.26±0.19 (8)	-0.31±0.16 (9)	-0.17±0.02 (3)
Ti I	-0.25±0.13 (31)	-0.15±0.17 (46)	-0.15±0.21 (21)
Ti II	-0.33±0.09 (3)	-0.06±0.16 (5)	-0.19±0.09 (2)
V I	-0.03±0.13 (16)	-0.11±0.12 (22)	-0.25±0.17 (18)
V II	-0.09±0.12 (3)	-0.35±0.17 (3)	-0.09±0.02 (2)
Cr I	-0.31±0.22 (16)	-0.25±0.18 (26)	-0.33±0.17 (9)
Cr II	+0.03±0.05 (4)	-0.40±0.21 (8)	-
Mn I	-0.18±0.16 (9)	-0.26±0.17 (10)	-0.47±0.11 (2)
Fe I	-0.26±0.11(132)	-0.24±0.16(182)	-0.20±0.16(116)
Fe II	-0.18±0.18 (9)	-0.22±0.19 (10)	-0.19±0.07 (5)
Co I	-0.07±0.15 (9)	-0.26±0.17 (11)	-0.16±0.19 (6)

Table 4. continued

Element	HD 155410	HD 160538	HD 166478
Ni I	-0.20±0.16 (31)	-0.35±0.14 (37)	-0.19±0.16 (23)
Cu I	-0.19 (1)	-0.20±0.02 (2)	-
Y I	-0.24 (1)	-0.12±0.10 (4)	-0.27±0.07 (3)
Y II	-0.24±0.18 (3)	-0.38±0.23 (3)	-
Zr I	-0.67±0.10 (4)	-0.24±0.12 (4)	-0.55±0.15 (3)
Zr II	-0.11 (1)	-0.43±0.09 (2)	-
Ba II	-0.29±0.11 (3)	-0.02±0.03 (3)	+0.06±0.05 (2)
La II	-0.15±0.09 (5)	-0.27±0.07 (4)	-0.16±0.05 (2)
Ce II	-0.15 (1)	-0.46±0.15 (4)	-
Pr II	-0.10 (1)	-0.19 (1)	-
Nd II	-0.10±0.12 (4)	-0.36±0.18 (5)	-0.27 (1)
Eu II	-	-0.41 (1)	-0.17 (1)

Element	HD 168532	HD 170737	HD 176155
C I	+0.14 (1)	-0.87 (1)	-0.35±0.02 (2)
O I	-0.28 (1)	-0.49 (1)	-
Na I	-0.08±0.03 (2)	-0.92±0.04 (3)	-0.08±0.03 (2)
Mg I	-0.16±0.18 (4)	-0.52±0.25 (4)	-0.11±0.19 (3)
Si I	-0.08±0.13 (8)	-0.76±0.15 (10)	-0.21±0.11 (9)
Ca I	-0.23±0.15 (13)	-0.52±0.21 (16)	-0.22±0.12 (10)
Sc I	-0.16 (1)	-	-
Sc II	-0.28±0.16 (7)	-0.74±0.18 (10)	-0.23±0.12 (7)
Ti I	-0.18±0.16 (43)	-0.68±0.16 (40)	+0.06±0.15 (10)
Ti II	-0.35±0.04 (5)	-0.56±0.26 (6)	-0.20±0.21 (3)
V I	-0.06±0.16 (17)	-0.90±0.14 (18)	-0.13±0.16 (7)
V II	-0.02±0.09 (2)	-0.62±0.11 (2)	-0.30±0.16 (3)
Cr I	-0.24±0.19 (21)	-0.99±0.20 (20)	-0.04±0.19 (7)
Cr II	0.00±0.08 (3)	-1.09±0.11 (7)	-0.51±0.20 (5)
Mn I	-0.18±0.22 (10)	-1.26±0.10 (8)	-0.54±0.12 (8)
Fe I	-0.21±0.15(146)	-0.85±0.18(187)	-0.18±0.12(105)
Fe II	-0.16±0.19 (8)	-0.99±0.21 (11)	-0.19±0.17 (9)
Co I	-0.10±0.13 (10)	-0.79±0.12 (9)	-0.18±0.09 (3)
Ni I	-0.27±0.17 (32)	-0.88±0.20 (34)	-0.20±0.18 (23)
Cu I	-0.12±0.20 (3)	-0.94±0.11 (2)	-
Zn I	-	-0.77 (1)	-
Y I	-0.12±0.04 (2)	-	+0.48±0.04 (2)
Y II	-0.29±0.08 (6)	-0.75±0.04 (2)	-0.29±0.04 (3)
Zr I	-0.54±0.18 (5)	-0.74±0.00 (2)	+0.50±0.21 (3)
Zr II	-0.07±0.05 (2)	-1.27±0.11 (2)	-
Ba II	+0.07±0.06 (3)	-0.98±0.12 (3)	+0.24±0.15 (2)
La II	-0.08±0.08 (4)	-0.97±0.27 (3)	-0.45±0.11 (4)
Ce II	-0.03±0.07 (2)	-0.78±0.11 (3)	+0.07±0.06 (3)
Pr II	-0.03±0.14 (2)	-0.59±0.22 (2)	-0.26 (1)
Nd II	+0.07±0.16 (7)	-0.84±0.29 (5)	-0.18±0.15 (5)
Eu II	-0.24 (1)	-	-0.11 (1)

Element	HD 176524	HD 179558	HD 181602
C I	0.00 (1)	+0.02±0.05 (2)	-0.12 (1)
O I	-	-	+0.09 (1)
Na I	-0.22±0.00 (2)	-0.01±0.08 (3)	-0.10±0.01 (3)
Mg I	-0.12±0.10 (3)	+0.11±0.16 (4)	-0.16±0.08 (4)
Si I	-0.13±0.09 (9)	0.00±0.09 (12)	-0.11±0.11 (14)
Ca I	-0.17±0.14 (13)	+0.04±0.21 (17)	-0.08±0.08 (15)
Sc I	+0.03 (1)	-	-
Sc II	-0.20±0.16 (7)	-0.02±0.20 (9)	-0.13±0.08 (10)
Ti I	-0.22±0.11 (32)	+0.07±0.15 (14)	-0.13±0.19 (10)
Ti II	-0.27±0.10 (3)	-0.07±0.23 (4)	-0.18±0.12 (4)
V I	-0.17±0.09 (18)	+0.01±0.14 (8)	-0.14±0.08 (4)
V II	+0.07±0.08 (3)		+0.05 (1)
Cr I	-0.20±0.18 (15)	+0.02±0.20 (12)	-0.06±0.10 (9)
Cr II	-0.23±0.15 (5)	-0.01±0.15 (6)	-0.21±0.03 (5)
Mn I	-0.11±0.18 (10)	+0.37±0.19 (9)	-0.18±0.20 (6)
Fe I	-0.16±0.13(145)	+0.02±0.17(146)	-0.11±0.10(123)
Fe II	-0.26±0.13 (9)	-0.14±0.20 (12)	-0.12±0.13 (13)
Co I	-0.14±0.10 (9)	+0.05±0.17 (5)	-0.15±0.11 (3)
Ni I	-0.25±0.18 (29)	-0.02±0.15 (22)	-0.12±0.13 (30)
Cu I	-	-0.09±0.09 (2)	-0.23±0.11 (3)
Y I	-0.17±0.09 (2)	-	-
Y II	-0.24±0.03 (3)	-0.21±0.25 (4)	-0.16±0.10 (5)
Zr I	-0.43±0.08 (4)	-	-
Zr II	-0.38 (1)	-	-
Ba II	-0.03±0.09 (3)	-0.19±0.18 (3)	-0.08±0.04 (2)
La II	-0.21±0.16 (4)	-0.19 (1)	-
Ce II	-0.04±0.02 (2)	-	-0.21±0.25 (3)
Pr II	-0.01 (1)	-	+0.01 (1)
Nd II	+0.03±0.10 (4)	-	-0.04±0.10 (3)
Eu II	+0.21 (1)	-	-

Element	HD 204934
Na I	+0.07±0.14 (3)
Mg I	+0.13±0.09 (4)
Si I	+0.09±0.11 (11)
Ca I	+0.09±0.18 (18)
Sc II	-0.02±0.16 (11)
Ti I	+0.02±0.14 (45)
Ti II	+0.08±0.14 (6)
V I	+0.09±0.09 (22)
V II	-0.07±0.17 (2)
Cr I	-0.10±0.15 (27)
Cr II	-0.13±0.15 (8)
Mn I	+0.01±0.16 (10)
Fe I	+0.01±0.15(210)
Fe II	-0.05±0.12 (10)
Co I	+0.02±0.17 (11)
Ni I	-0.04±0.14 (43)
Cu I	-0.25±0.05 (2)
Zn I	-0.03 (1)
Y I	-0.13±0.19 (5)
Y II	-0.34±0.09 (5)
Zr I	-0.12±0.10 (4)
Zr II	-0.01 (1)
Ba II	-0.20±0.07 (3)
La II	-0.11±0.16 (3)
Ce II	-0.24±0.20 (3)
Pr II	-0.01±0.06 (2)
Nd II	-0.17±0.13 (6)
Eu II	-0.16±0.02 (2)

case of DR Dra, at least some of the analyzed systems contain a WD companion, because according to Jorissen & Boffin (1992) unevolved systems never populate the right-bottom corner on the $(e - \log P)$ plane (Fig. 9). Part of the analyzed single-lined primaries fulfill three constraints: 1) $200 < P(\mathrm{days}) < 6000$, (2) $f(M) \leq 0.1\ M_\odot$, and (3) $e < e_{\mathrm{Ba}}(P)$, where $e_{\mathrm{Ba}}(P)$ is the maximum eccentricity observed at period P among barium systems (Jorissen & Boffin 1992). Constraint (1) ensure that the considered systems followed the same binary evolution as barium stars. Constraint (2) allows to get rid of systems with massive main sequence companions, while systems not fulfilling constraint (3) are likely unevolved and therefore contain a main sequence rather than a WD companion. Thus the detailed abundance analyses show that the presence of WD companions in barium stars-like binaries is not sufficient to produce a strong barium star. This conclusion confirmed especially the chemical composition of DR Dra (K0III, $P = 903.8$ days) with a directly confirmed WD companion from IUE spectra (Fekel & Simon 1985).

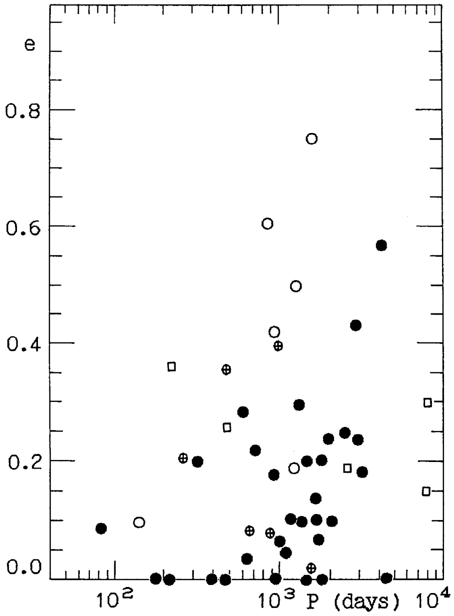

Fig. 9. Diagram $(e,\ \log P)$ for single-lined spectroscopic binaries with barium star like orbital elements. Filled circles (●): barium stars from Jorissen & Boffin (1992); open circles (○): giants showing normal barium abundance; crossed circles (⊕): giants showing mild barium enhancement; squares (□): dwarfs

At the same time five of the analyzed giants (5 Tau, DR Dra, HD 166478, HD 168532, HD 176524) show a mild enhancement ([Ba/XII] = 0.2 − 0.3 dex) of the s-process element barium (see Table 3). Although the barium abundance is based only on three BaII lines, a careful analysis shows that this effect has not a methodical nature, because:

1) The Ba II lines have a medium intensity (120−250 mÅ);
2) The standard deviation of barium abundances obtained from three BaII lines does not exceed usually 0.1 dex (0.08 for 5 Tau, 0.03 for DR Dra, 0.06 for HR 6860, and 0.09 for HR 7180);
3) Non-LTE effects in BaII lines are small (Mashonkina & Začs 1996) and our differential line by line analysis relative to the similar standard canceled possible slight (< 0.1 dex) non-LTE deviations;
4) Some of the analyzed BaII star like giants (with similar atmospheric structure) show a normal barium abundance.

This conclusion support the location of the barium enhanced binaries on the $(e, \log P)$ plane (see Fig. 9). As can be seen, barium enhanced giants occupy a place on the diagram similar to BaII stars. In the right-bottom corner only dwarfs and one giant HR 5053 (K0III, $P = 1366.8$ days) from our program stars have a normal barium abundance. However, the unseen companion of HR 5053 is a G-dwarf ($f(M) = 0.47$, Batten et al. 1989). We included this star in the observations program to test the possible influence (due to tidal mixing, as has been sometimes suggested) of a main sequence companion on the atmospheric structure (chemical composition) of the primary (giant) star in BaII star like systems. Since the atmosphere of HR 5053 does not show any peculiarities of chemical composition we concluded that the main sequence companion does not have a significant influence on the internal structure of the primary star. On the other hand, on the $(e,\ \log P)$ plane outside the region occupied by barium star we do not find any peculiar (barium enhanced) primary in our sample of barium stars like binaries. Therefore, we come to the conclusion that a mild barium enhancement in five giants is, presumably, a result of mass transfer from the companion during its late phases of evolution. Thus it seems likely that all red giant spectroscopic binaries (primaries) in barium star like systems with WD secondaries have chemical peculiarities of barium (s-process elements). The degree of chemical peculiarities of the primary depends, apparently, on the efficiency of mass transfer in a specific binary system.

We certainly do not apply this conclusion to the supergiant FN Aql because:

1) The BaII lines in the spectra of this star are substantially stronger than for giants (269 mÅ for BaII line at λ5863.68 Å);
2) The atmospheric structure of supergiants is significantly different from the standard giant, therefore, differential analysis might not cancel possible (greater) non-LTE effects.

Our observational program includes also two mild barium stars HD 119185 (Ba 1.0) and HD 130255 (Ba 1.0) from Jorissen's (1994) list, that did not show radial velocity (RV) variations. We obtained [s/XII] = +0.50 dex for HD 130255 and [s/XII] = +0.22 dex for HD 119185. The significant enhancement of s-process elements is shown by both stars. However, we would like to note that due to the higher dispersion of the chemical abundances obtained from different lines, the error of the derived atmospheric parameters and abundances for HD 130255 is higher than for other program stars. The s-process enhancement of RV non-variable barium stars confirms a previous conclusion (Začs 1994) that these barium stars, probably, have either velocity variations below the limit of detection (very long orbital period), or high inclined orbital planes.

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