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Abundance analysis of Am binaries and search for tidally driven abundance anomalies – II. HD 861, HD 18778, HD 20320, HD 29479, HD 96528 and HD 108651

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ABSTRACT

The main goal of this paper is to continue a systematic abundance analysis of a sample of Am binaries in order to search for possible abundance anomalies driven by tidal interaction in these binary systems.

New CCD observations in two spectral regions (6400–6500 and 6660–6760 Å) of HD 861, HD 18778, HD 20320, HD 29479, HD 96528 and HD 108651 were obtained. Synthetic spectrum analysis was carried out, and basic stellar properties, effective temperatures, gravities, projected rotational velocities, masses, ages and abundances of several elements were determined. We conclude that HD 861, 29479 and 108651 are typical Am stars, while HD 20320 and 96528 are mild Am stars. HD 18778 turned out not to be an Am star although its projected rotational velocity is very low (27 km s^{-1}). On the contrary, HD 96528 has one of the highest projected rotational velocities (85 km s^{-1}) among Am binaries with orbital periods in the range 20–200 d, and yet it exhibits Am anomalies. Pseudo-synchronization and abundance anomalies are discussed in the context of possible tidal effects.

Key words: diffusion – hydrodynamics – stars: abundances – binaries: close – stars: chemically peculiar.

1 INTRODUCTION

The Am stars is a well-known subgroup of chemically peculiar (CP) stars on the upper main sequence (MS). They exhibit abnormally strong metallic and unusually weak Ca and Sc lines, and, as a consequence, the spectral types inferred from calcium lines are usually earlier than those from hydrogen lines, and the latter are earlier than the spectral types from the metallic lines. The anomalous intensity of most of these absorption lines is due to the abnormal chemical composition of superficial layers. The typical abundance pattern of Am stars is that they exhibit a deficit of light elements like C, Mg, Ca, Sc and progressively increasing overabundances of iron group and heavier elements. This abundance pattern is often referred to as the Am phenomenon. Rotation was found to play a key role in these stars, and there is a growing amount of recent observational evidence that Am peculiarity is either a smooth or a step function of rotation (Hauck & Curchod 1980; Abt & Morrell 1995; Savanov 1995; Takeda & Sadakane 1997; Varenne & Monier 1999; Abt 2000; Burkhart & Coupry 2000; Feňovčík et al. 2004). Nevertheless, Am peculiarity does seem to depend on evolutionary status or age as well. It may (i) develop very quickly soon after the star arrives on the MS, or even before that (Burkhart & Coupry 2000), and does not undergo considerable changes during the MS phase, or (ii) observable abundances of some elements may vary with age and this can be used to constrain the evolutionary models (Monier & Richard 2004; Monier 2005). At the same time, no significant correlation of the abundance anomalies with $v \sin i$ was found by Monier & Richard (2004) and Monier (2005). Apart from that, the Am phenomenon is apparently restricted to a well-defined region of the MS in the Hertz sprung–Russell (HR) diagram which implies its dependence on atmospheric parameters such as effective temperature and gravity (Künzli & North 1998; Hui-Bon-Hoa 2000).

The Am peculiarity seems to depend on the orbital elements in a binary system as well. Budaj (1996, 1997a,b), Iliev et al. (1998) and Feňovčík et al. (2004) studied $v \sin i$ versus $P_{\rm orb}$, e versus $P_{\rm orb}$, δm_1 versus $P_{\rm orb}$, $f(m)$ versus $P_{\rm orb}$, $v \sin i$ versus $P_{\rm p}$ and δm_1 versus $P_{\rm p}$, where $P_{\rm orb}$ is the orbital period, $f(m)$ is a mass function and $P_{\rm p}$ is the 'instantaneous' orbital period at periastron.[1] The orbital period distribution (OPD), behaviour of δm_1 index in

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[1] It is the orbital period which the stars would have if they had a circular orbit with the same velocity and separation as at periastron. This quantity was invented only as a tool to study the effects of pseudo-synchronization. It should not be associated with the real period of the stars with the same mass on circular orbit.

the $v \sin i$ versus P_{orb} and $v \sin i$ versus P_{p} planes, behaviour of Ca, Fe and Li abundances and a number of other properties of Am binaries were studied as well. The authors concluded that there are a number of subtle effects which are difficult to understand within the current framework of the rotation and atmospheric parameters[2] as the only agents determining the Am star peculiarity. For example, it was argued by Budaj (1996) that the short period cut-off in the OPD of Am binaries at about 1.2 d may not be associated with the generally accepted maximum allowed rotation velocity of Am stars of about 100 km s^{-1} via the spin–orbit synchronization. This is because there is no reason to believe that the internal hydrodynamics and mixing in a tidally locked star in a short period binary is the same as in a single rotating star. It was suggested that the surface of the Am star acquires the Roche geometry as it approaches the Roche lobe and that the Am phenomenon might be destroyed by the Roche lobe overflow or, even before that, by the tidally induced currents competing with the diffusion, or by a number of other effects. The maximum allowed rotation for an Am star was found not to be a simple constant but a function of the orbital period. The Am phenomenon seems more pronounced in binaries with eccentric orbits and possibly also at longer orbital periods provided that the binary components are still within the reach of tidal effects. A tendency towards the spin–orbit pseudo-synchronization up to $P_{\mathrm{orb}} \approx 35$ d was unravelled. A complex study of these effects together with the study of the properties of Ap binaries (Budaj 1999) led the authors to suggest that the binary companion of an Am/Ap star could affect the mixing, hydrodynamics and magnetohydrodynamics of an Am/Ap star, and thus also the appearance of the Am/Ap phenomenon.

North & Debernardi (2004) studied e versus P_{orb} and the OPD of Am binaries and concluded that there are two populations of Am stars: (i) systems with $1 < P_{\mathrm{orb}} < 30$ d that owe their slow rotation to tidal effects and (ii) systems with $P_{\mathrm{orb}} > 30$ d, or single stars, for which tides are not effective. On the other hand, Noels, Montalbán & Maceroni (2004) reanalyzed the $v \sin i$ versus P_{orb} diagram of Budaj (1996) using recent values of $v \sin i$ from Royer et al. (2002) and concluded that there is no need for any extra mixing associated with the tidal interaction in binary systems to understand this diagram. In connection with these effects, the studies of individual Am binaries are very important (e.g. Iliev et al. 2001a,b; Griffin 2002; Mikulášek et al. 2004; Yushchenko et al. 2004; Frémat, Lampens & Hensberge 2005; Southworth et al. 2005). Ryabchikova (1998) concluded that all secondary stars in HgMn binaries with effective temperatures less than 10 000 K show abundance characteristics typical of the metallic-line stars. Vuissoz & Debernardi (2004) studied the distribution of mass ratio, q, in Am binaries and found that it is centred on $q = 0.56$. New orbital elements of many Am binaries were determined by Carquillat et al. (2003, 2004), Ginestet et al. (2003), Carquillat et al. (2002), Griffin & Griffin (2002), Debernardi (2002) and Carquillat, Ginestet & Prieur (2001).

Since Am stars are often found in binaries (North et al. 1998; Debernardi et al. 2000), they provide a unique opportunity to study the influence of a companion on the stellar hydrodynamics. The main aim of this paper is to study the Am peculiarity in multidimensional parameter space involving the orbital elements, $v \sin i$, mass and age, and to continue in such systematic spectroscopic investigation of Am binaries started in the first paper of this series by Budaj & Iliev (2003, hereafter Paper I).

2 OBSERVATIONS AND SAMPLE STARS

Our spectroscopic observations were carried out with the 2-m Ritchey–Chretien Coudé (RCC) telescope of the Bulgarian National Astronomical Observatory in the frame of our scientific project on Am stars in binary systems. We observed each star in two spectral regions: 6400–6500 Å (Ca) and 6660–6760 Å (Li) and focused on Ca I 6439 Å and the rich spectrum of iron lines. The photometrics AT200 camera with a SITe SI003AB 1024 × 1024 CCD chip (24 μm pixels) was used in the third camera of the Coudé spectrograph to provide spectra with a typical resolution of $R = 32\,000$ and signal-to-noise ratio (S/N) of about 300. The instrumental profile was checked and adjusted during each setup of instruments using the comparison spectrum so that its full width at half-maximum (FWHM) was about 0.2 Å and never exceeded this value. IRAF standard procedures were used for bias subtracting, flat-fielding and wavelength calibration. The telluric lines were removed using the spectra of hot, fast rotating stars. The wavelength calibration had a rms error of 0.005 Å. Two IAU radial velocity standard stars – ϕ Aql and 5 Ser – have also been observed during 2000–2004. The same setup of the spectrograph and the same spectral regions were used. Our measurements of radial velocities show no systematics beyond the typical error of 2 km s^{-1}. Similar result has been reported earlier by Iliev et al. (2002). The EQWREC2 code of Budaj & Komžík (2000) was also used for some tasks like continuum rectification. The abridged log of observations is displayed in Table 1.

A few tens of Am binaries from Seggewiss (1993) further restricted and studied by Budaj (1996) were chosen for more detailed spectroscopic analysis. Additional extraction criteria were applied to their sample to compile a list of targets for this work: targets brighter than the 7th magnitude in the V filter with declination $\delta > -10^{\circ}$. Only stars with orbital periods $10^{d} < P_{\mathrm{orb}} < 180^{d}$ will be considered initially. This assures a full range of original eccentricities which did not undergo circularization on the MS. No constraints were placed on the rotational velocity. The focus of this paper is to continue an analysis of another six stars from this sample, namely: HD 861, 18778, 20320, 29479, 96528 and 108651.

3 ATMOSPHERIC PARAMETERS AND SPECTRUM SYNTHESIS

Relevant information about our programme stars is summarized in Table 2. The $uvby\beta$ indices [de-reddened using the UVBYBETA code of Moon & Dworetsky (1985)] were taken from Renson (1991). Geneva and *UBV* photometry were from Rufener (1980) and Mermilliod, Mermilliod & Hauck (1997), respectively. All the stars were bright, and reliable parallaxes are known from the *Hipparcos* mission (ESA 1997). Table 2 also lists the absolute M_V magnitudes obtained from these parallaxes and V photometry. The atmospheric parameters were derived from both $uvby\beta$ and Geneva photometry. If both estimates were available, we accepted their rounded mean as the best choice for model atmosphere parameters.[3] In the case of $uvby\beta$ photometry, we used the TEFFLOGG code of Moon & Dworetsky (1985), but Smalley & Dworetsky (1995) was also consulted. In the case of Geneva photometry, we used the calibration of Kobi & North (1990) and also consulted Künzli et al. (1997). All these stars seem to be SB1 binaries or have only a very weak

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[2] Atmospheric parameters (T_{eff}, $\log g$) are determined by the mass and the age of the star.

[3] We refrained from using the diagrams of abundances versus excitation potential to determine atmospheric parameters since there are very few suitable absorption lines for this purpose.

Table 1. Log of observations: spectrum number, date (yyyy.mm.dd), HJD (245 0000+) of the beginning of the exposure, effective exposure time (min), spectral region, heliocentric radial velocity of the primary and its error (km s^{-1}).

No	Date	HJD	Exp.	Reg.	RV1	ΔRV1
			HD 861			
1	2001.01.11	1921.197	120	Li	+25.5	0.9
2	2001.08.31	2152.496	120	Ca	−25.9	1.6
3	2003.10.04	2917.280	90	Ca	−40.9	1.2
4	2003.10.04	2917.348	66	Ca	−40.4	1.0
5	2004.01.09	3014.206	55	Ca	−37.6	1.2
6	2004.02.07	3043.222	35	Ca	−25.0	1.4
			HD 18778			
1	2000.11.06	1855.360	100	Ca	−6.8	1.3
2	2000.12.12	1891.250	65	Li	−1.1	2.3
			HD 20320			
1	2001.01.10	1920.173	111	Ca	+6.0	1.5
2	2001.10.31	2214.449	60	Li	−9.6	4.8
			HD 29479			
1	2001.10.31	2214.492	50	Li	+17.0	6.1
2	2002.02.28	2334.209	70	Ca	−1.3	1.5
			HD 96528			
1	2002.02.27	2333.374	180	Li	+23.0	5.5
2	2002.02.28	2334.372	180	Ca	+17.5	1.5
			HD 108651			
1	2001.04.04	2004.417	60	Li	+3.7	1.7
2	2001.06.10	2071.282	40	Ca	+1.6	0.9

secondary spectrum (HD 861), hence the possible influence of their companions on photometry was neglected.

A detailed spectrum synthesis of the spectral regions was accomplished using the code SYNSPEC (Hubeny, Lanz & Jeffery 1994; Krtička 1998). Model atmospheres were interpolated from Kurucz (1993a). The Vienna atomic line data base (VALD) (Kupka et al. 1999), which also contains Kurucz (1993b) data, was used to create a line list for the spectrum synthesis. Over 2000 lines were used in each spectral region. Unfortunately, the accuracy of the atomic data is still not sufficient and the above-mentioned data were complemented by data from Paper I who calibrated many gf-values on the solar spectrum.

The iron abundance was first determined from weak Fe lines, and the microturbulent velocity was used as a free parameter to obtain a fit for the stronger Fe lines. The computed spectra were convolved with the instrumental profile (Gaussian of 0.2 Å FWHM) and rotationally broadened to fit the observed spectra.

4 RESULTS

The abundances obtained by synthetic spectrum fitting analysis are expressed relative to the Sun in terms of $[\mathrm{N/H}] = \log(N/H)_\star - \log(N/H)_\odot$ in Table 3. Taking into account the accuracy of the atmospheric parameters, as well as the atomic data, the abundances of Al, Si, S, Ca and Fe are generally determined within $\lesssim$0.2 dex, while the abundances of the other elements, which mainly occur in weak blends, are only approximate. The Ba abundances should be used with caution as they are usually derived from only one line (Ba II 6497 Å), which is at the edge of our frames. Apart from abundances and atmospheric parameters, we also derived the basic stellar properties like mass and age. We determined the observed absolute magnitudes from the known parallaxes, created an HR diagram and interpolated the evolutionary tracks and isochrones of Lejeune & Schaerer (2001). The masses, ages and expected terminal-age main sequence (TAMS) obtained are also listed in Table 3, and the position of our programme stars in the HR diagram is illustrated in Fig. 1. Both the synthetic and observed spectra are depicted in Figs 2 and 3.

Radial velocities, projected rotational velocities and microturbulent velocities were also determined as by-products and are listed in the Tables 1 and 3. A comparison between measured radial velocities of the six stars and predicted radial velocity curves is shown in Fig. 4. For the Am stars with $v \sin i < 50$ km s^{-1}, the radial velocities of the primary stars were measured using the cross-correlation of the whole spectral region of the observed spectrum with the synthetic spectra. For highly rotating stars (HD 20320, 29479, 96528) with $v \sin i > 50$ km s^{-1}, the cross-correlation technique produces large errors due to heavy line blending in some spectral regions. Consequently, in the Li region, we restricted the cross-correlation region to 6710–6765 Å, and in the Ca region, we measured the velocities from the Ca I 6439 Å line using the centre of mass method. The measurements of Paper I with the same telescope configuration and centre of mass method demonstrated, on the example of highly rotating star (HD 178449, $v \sin i = 139$ km s^{-1}), that the standard deviation of such radial velocity measurements was less than 2 km s^{-1}. A discussion of the individual stars follows.

4.1 HD 861

This star (HD 861, SAO 11044, HIP 1063, BD +61 16) is a well-known spectroscopic binary of the SB1 type but has been rarely studied although it is quite bright and close. Duflot & Fehrenbach (1956a) and Duflot & Fehrenbach (1956b) mentioned that it has variable radial velocities. First orbital elements were determined by Acker (1971) from 14 observations combined with three additional older observations of Boulon (1956) and Boulon (1957). Very different orbital elements were determined recently by Debernardi (2002) who also discovered the secondary spectrum which implies mass ratio of about 2.12. Its orbital elements are $P_{\mathrm{orb}} = 15.9696^d$, $K_1 = 38.1$ km s^{-1}, $K_2 = 80.6$ km s^{-1}, $e = 0.124$, $V_0 = 1.5$ km s^{-1}, $\omega = 195\overset{\circ}{.}0$ and $T_0 = 245\,0010.90$. The star was classified as an A2 star based on the Ca II K line and as an F2 star based on the metallic lines by Slettebak & Nassau (1959). Calcium was found to be underabundant by about 0.4 dex by Künzli & North (1998) who also determined the following parameters: $v \sin i = 35$ km s^{-1}, $\xi_{\mathrm{turb}} = 3.2$ km s^{-1}, $T_{\mathrm{eff}} = 7715$ K, $\log g = 3.9$. The photometric data base of Mermilliod et al. (1997) lists the *UBV* observations of Bouigue, Boulon & Pedoussaut (1961) $V = 6.64$ mag, $B - V = 0.19$ mag. Budaj et al. (2004) independently detected the secondary spectrum and derived the mass ratio which is in agreement with Debernardi (2002).

The Fe II and Fe I lines in the spectra suggest that the temperature of the primary star could be a few hundred degrees higher than the temperature derived from the Geneva photometry. This might be due to a weak dilution of the photometric indexes by the cooler

Table 2. Photometry, atmospheric parameters and other relevant information about the observed stars.

Star	HD 861	HD 18778	HD 20320	HD 29479	HD 96528	HD 108651
V	6.640	5.948	4.797	5.070	6.494	6.635
B-V	0.190	0.149	0.232	0.146	0.163	0.216
U-B	–	0.090	0.083	0.190	0.120	0.084
E(b-y)	–	–	−0.005	−0.002	0.014	0.006
$(b-y)_0$	–	–	0.138	0.058	0.079	0.114
m_0	–	–	0.190	0.224	0.214	0.233
c_0	–	–	0.846	0.992	0.912	0.832
β	–	–	2.795	2.887	2.870	2.843
$T_{\rm eff}$	–	–	7650	8460	8330	8100
$\log g$	–	–	3.97	4.09	4.24	4.35
B2-V1	−0.003	−0.028	0.023	−0.064	−0.040	0.011
d	1.328	1.307	1.237	1.353	1.287	1.206
$T_{\rm eff}$	7715	8144	7751	8474	8297	7914
$\log g$	4.12	4.03	3.97	4.07	4.16	4.17
$P_{\rm orb}$	16.0[1]	11.7[2]	17.9[3]	39.0[3]	40.4[4]	68.3[6]
e	0.12[1]	0.29[2]	0.14[3]	0.15[3]	0.08[5]	0.30[6]
π	8.55 ± 0.63	16.13 ± 0.53	27.18 ± 0.97	21.49 ± 0.96	13.23 ± 0.93	12.66 ± 0.93
M_V	1.30/5.62	1.99	1.97	1.73	2.10	2.15
		Adopted atmospheric parameters				
$T_{\rm eff}$	8100	8140	7700	8470	8310	8010
$\log g$	4.00	4.03	3.97	4.08	4.20	4.26

Note: [1]Debernardi (2002); [2]Abt (1961); [3]Abt & Levy (1985); [4]Heard (1937); [5]Lucy & Sweeney (1971) and [6]Abt & Willmart (1999). $T_{\rm eff}$ is in [K], $\log g$ in CGS units, $P_{\rm orb}$ in days and π in (mas).

Table 3. Abundances derived in terms of [N/H] for our six stars. Abundances of the Sun are in terms of $\log(N_{\rm el}/N_{\rm H}) + 12.00$.

	Sun	HD 861	HD 18778	HD 20320	HD 29479	HD 96528	HD 108651
Li	1.10	⩽+2.08	+2.24	+2.01	⩽+2.05		+2.01
C	8.52	⩽−0.34	−0.20	⩽−0.41	⩽−0.62	⩽−0.29	⩽−0.44
O	8.83	⩽−0.15	−0.05	⩽−0.30	−0.11		⩽−0.20
Al	6.47	+0.24	−0.05	⩽−0.36	⩽+0.27	+0.33	+0.16
Si	7.55	+0.07	+0.24	−0.07	+0.26	+0.07	+0.22
S	7.33	+0.09	−0.15	+0.07	+0.12	+0.08	−0.15
Ca	6.36	−0.30	+0.21	−0.53	−0.36	−0.41	−0.52
Ti	5.02	−0.07	+0.28	⩽−0.07	+0.38	+0.26	+0.28
Fe	7.50	+0.44	+0.15	−0.08	+0.36	+0.12	+0.45
Ni	6.25						≈+0.71
Ba	2.21	+2.64			+1.77	+1.17	+2.07
$\xi_{\rm turb}$	–	2.2	2.4	2.7	2.6	2.5	2.3
$v \sin i$	–	37	27	68	59	85	21
M	–	2.04/0.95	1.82	1.78	1.94	1.82	1.77
$\log T$	–	8.86	8.72	8.93	8.68	8.45	8.67
log TAMS	–	9.02	9.18	9.21	9.09	9.18	9.21

Note: Sun: abundances are taken from Grevesse & Sauval (1998) (recall that normal lithium abundance in hot stars or meteorites is [Li/H] = 2.00); microturbulence – $\xi_{\rm turb}$ and $v \sin i$ are in km s^{-1}, M is mass in $M_\odot$, T and TAMS are age in years.

companion. The atmospheric models with effective temperatures 8000–8250 K seem to represent the observed spectrum best, and in this particular case we adopted spectroscopic atmospheric parameters: $T_{\rm eff} = 8100$ K, $\log g = 4.0$. Some strong Fe II lines indicate even higher temperature or higher microturbulence.

The abundance pattern is typical of an Am star. Lithium was detected but its abundance is most likely an upper limit. C, O and Ca are underabundant, and we were able to derive only reliable upper limits for the C and O abundances. The Si, S, Ti abundances are normal. Fe is overabundant but Ba seems extremely overabundant. Aluminium is slightly overabundant but its abundance is slightly anti-correlated with Si abundance since the Al lines are blended with Si lines. Ni and Eu seem overabundant as well but their abundances are very uncertain due to the heavy blending. HD 861 is thus a typical

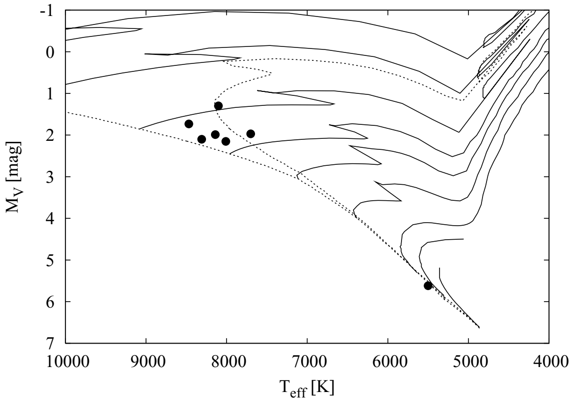

Figure 1. The location of our six stars in the HR diagram. The star at the bottom is a 'b' component of HD 861. Evolutionary tracks for $M = 3.0$, 2.5, 2.0, 1.7, 1.5, 1.25, 1.0, 0.9 and 0.8 $M_\odot$ are shown by solid lines, isochrones for $\log T = 3.0$ and 8.85 (in yr) are shown by dotted lines (Lejeune & Schaerer 2001).

Am star and its abundance anomalies seem to be consistent with its projected rotational velocity as well as the orbital elements.

We carried out additional calculations of synthetic spectra and found that the sharp (secondary) spectrum was well reproduced by the following atmospheric parameters: $T_{\rm eff} = 5500$ K, $\log g = 4.5$ and light ratio $L_a/L_b = 43$ (we assumed a solar chemical composition, $v \sin i = 2$ km s^{-1} and $\xi_{\rm turb} = 1$ km s^{-1}). These properties correspond to a G dwarf which is about 4.1 mag fainter than the primary star at 6450 Å. Using the above stellar models, we can predict the light ratio at 5500 Å (equivalent to V magnitude) to be $L_a/L_b = 54$ corresponding to $\Delta m_V = 4.3$ mag. We combined the synthetic spectrum of the primary with that of the secondary with the appropriate light ratio and Doppler shift and displayed it in Fig. 3. The position of this stellar companion ('b' component) in the HR diagram is illustrated in Fig. 1. It is located close to the zero-age main sequence (ZAMS) in perfect agreement with the position of a star with mass of about 0.95 $M_\odot$, and the positions of both 'a' and 'b' stars can be bridged by an isochrone. This location of the 'b' component in the HR diagram also confirms that the estimated temperature and luminosity ratio of the secondary star are plausible. The mass ratio derived from the evolutionary models and HR diagram ($M_a/M_b = 2.1$) is in perfect agreement with the mass ratio determined from the Doppler shifts of both sets of lines by Debernardi (2002) and Budaj et al. (2004). Our radial velocity measurements (see Fig. 4) also rule out the orbital elements of Acker (1971) and confirm the new orbital elements obtained by Debernardi (2002). The values for $v \sin i$ and $\xi_{\rm turb}$ that we obtained are roughly in agreement with the previous estimates of Künzli & North (1998). However, their temperature seems too low, which explains why they obtained slightly higher calcium underabundance.

4.2 HD 18778

HD 18778 (HR 906, HIP 14844, BD+8097, SAO 500, A7 III-IV, IDS 02562+8105, ADS 2348) is a triple system. The A and B are visual binary components separated by ~24 arcsec (Tokovinin 1997). The B component is considerably fainter (10.7 mag in the V band). The star is a member of the Ursa Major group.

The A component is a spectroscopic binary star (SB1). Roman (1949) classified it for the first time as an Am star. Later, Cowley et al. (1969) described it as a normal A star. Smith (1971) made a detailed curve-of-growth analysis in order to obtain the abundances of a group of Am stars and found that HD 18778 might be a link between marginal Am stars and normal A stars. Abt (1961) determined the period $P_{\rm orb} = 11.665^d$, eccentricity $e = 0.29$, $K = 4.5$ km s^{-1}, and other orbital elements of the star, and classified it as A7/A7/F2 from the Ca II K/hydrogen/metallic lines, respectively. The projected rotational velocity measured by Abt & Morrell (1995) was $v \sin i = 43$ km s^{-1}. However, Royer et al. (2002) obtained $v \sin i = 26$ km s^{-1}.

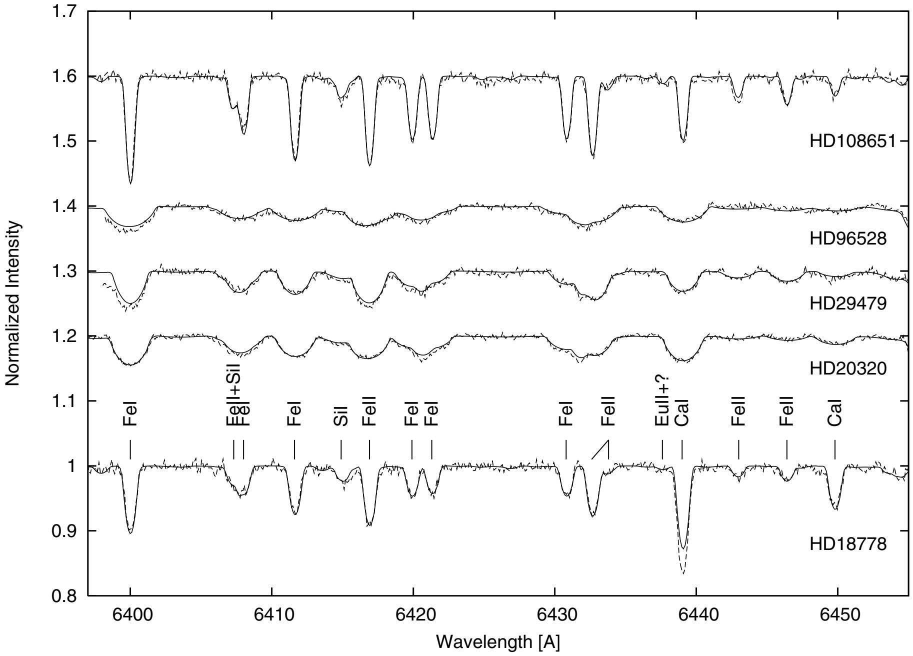

Figure 2. Synthetic (solid) and observed (dashed) spectra of five of our programme stars. The observed spectra were shifted to the laboratory frame of synthetic spectra. A proper shift to the vertical coordinate was applied to all but the lowest spectrum.

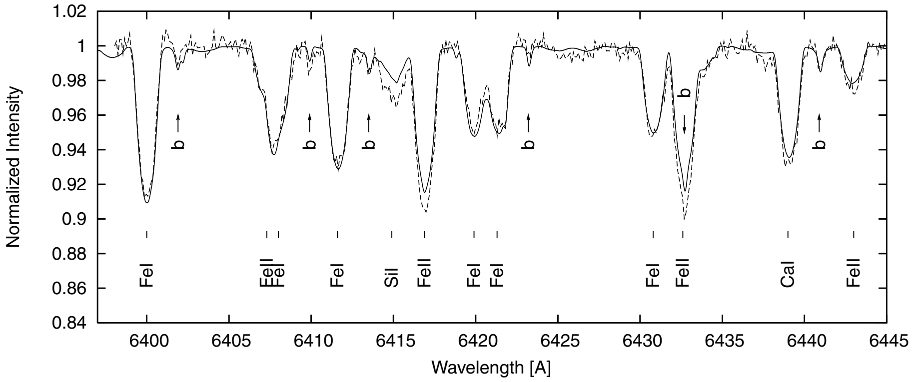

Figure 3. Observed spectrum of HD 861 (dashed line), synthetic spectrum (solid line). Note the sharp secondary spectrum in both observed and synthetic spectra denoted by an arrow and ‘b’. The observed spectrum was shifted in wavelength so that the primary, ‘a’, component has zero radial velocity.

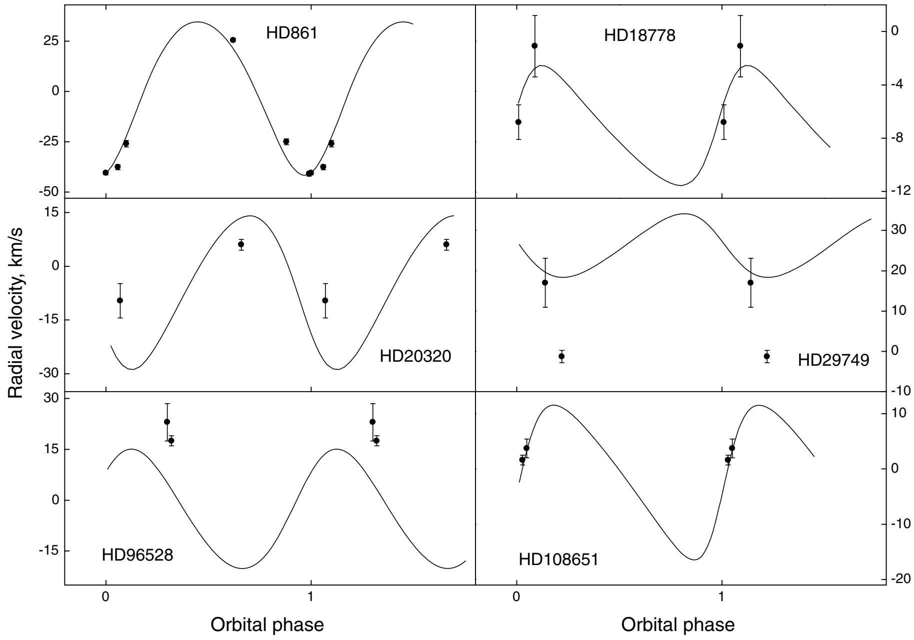

Figure 4. Measured radial velocities as listed in Table 1 (dots) in comparison with the predicted radial velocity curves (solid lines). Orbital elements are taken from the appropriate references shown in Table 2.

The iron spectrum of this star can be reproduced fairly well. However, the observed strong Ca lines are deeper than predicted by the synthetic spectrum. Consequently, abundances from weak and strong Ca lines differ and/or indicate a higher microturbulence than that derived from the Fe lines. The Fe and Ca abundances are normal. Ca may be even slightly enhanced and this is certainly not an Am star feature. The abundance anomalies of the other elements studied are also very mild. Li has a mild overabundance compared to the cosmic Li abundance. C is normal or in mild deficit based on the C I 6655 Å line (the gf-value of this line was refined by modelling the solar spectrum). Oxygen, aluminium and sulphur are normal. There may be mild Si and Ti overabundance.

We conclude that HD 18778 is not an Am star. However, the star has sharp lines, and the projected rotational velocity is rather small. Also, the eccentricity and orbital period do not rule out larger Am anomalies. HD 18778 is not very far from the ZAMS, but other Am stars like HD 96528 are even younger. They have much higher projected rotational velocities and still exhibit the Am phenomenon. Neither its $\log g$ nor the position in the HR diagram supports its classification as a giant or subgiant. One would expect to observe the Am star anomalies, unless the true rotational velocity is much higher, and we see the star almost pole on. This may indeed be the case since the K-value of the orbit is very small. This suggests that the orbit is highly inclined, and if the rotational and orbital axes are parallel this would support the idea of much higher equatorial rotation velocity of this star. Another possible explanation of the mild but strange abundance anomalies and spectrum is that the star could have a relatively bright FV-type companion, which is difficult to disentangle from the primary spectrum if the orbit is highly inclined and the rotation velocities are similar. Our radial velocity measurements definitely confirm that the velocities are variable and within their errors agree with the original RV curve of Abt (1961) (see Fig. 4). We cannot confirm the value of the $v \sin i$ given by Abt & Morrell (1995); our value is in perfect agreement with that obtained by Royer et al. (2002).

4.3 HD 20320

HD 20320 (ξ Eri, HR 984, BD–09 624, HIP 15197, SAO 130387) is a well-known spectroscopic binary star. There are different estimates of its spectral class in the literature. According to Slettebak (1955), it is an A2/A7 star based on the Ca II K/metallic lines, respectively. Later, Cowley et al. (1969) determined HD 20320 as an Am star. Vogt et al. (1998) classified it as an A5m star. The projected rotational velocity according to Slettebak (1955) is $v \sin i = 65\,\mathrm{km\,s^{-1}}$, which was later revised by Levato (1975) to $v \sin i = 70\,\mathrm{km\,s^{-1}}$. Abt & Morrell (1995) found $v \sin i = 71\,\mathrm{km\,s^{-1}}$. Royer et al. (2002) scaled the above value to their system and obtained $v \sin i = 82\,\mathrm{km\,s^{-1}}$. Abt & Levy (1985) determined the following orbital elements: $P_{\mathrm{orb}} = 17.9297^d$, $K = 21.5\,\mathrm{km\,s^{-1}}$, $e = 0.14$, $V_0 = -5.8\,\mathrm{km\,s^{-1}}$ and $\omega = 122\overset{\circ}{.}0$. Guthrie (1987) derived the abundances of Ca as log N(Ca) = 6.01 on a scale with log N(H) = 12.00 based on a differential curve-of-growth analysis. He obtained the following atmospheric parameters of the star: $T_{\mathrm{eff}} = 7700\,\mathrm{K}$, $\log g = 4.0$. Smalley & Dworetsky (1993) determined the atmospheric parameters of the star: $T_{\mathrm{eff}} = 7650\,\mathrm{K}$, $\log g = 4.0$. Comparison with the results of other authors show a difference in T_{eff} and $\log g$ within ± 200 K and $\pm$ 0.2 dex, respectively.

This star seems to have a normal Li content but the Li line is unusual and seems to be shifted to the red. C and O are in deficit, and we were able to establish only upper limits. Aluminium was surprisingly in the deficit and Ca was also underabundant. Si, S and Fe are normal. Ti may be normal but its abundance is rather an upper limit. We conclude that it is a mild Am star. This star exhibits broad lines and high rotation as well as low eccentricity. These properties prohibit building of more pronounced Am anomalies in agreement with the observed abundance pattern. This star is the coolest among the six stars studied in this paper and has the highest microturbulence, although reasonable. Our rotational velocity is in agreement with those obtained by Slettebak (1955), Levato (1975) and Abt & Morrell (1995), but the scaling of rotational velocities by Royer et al. (2002) does not seem to work well for this star. There is a kind of disagreement between our radial velocities and those predicted by the radial velocity curve of Abt & Levy (1985). This could be due to the uncertainty in the orbital phase accumulated over the time (see Fig. 4).

4.4 HD 29479

HD 29479 (91 Tau, HR 1478, BD+15 665, HIP 21673, SAO 94051, A4m) is a spectroscopic binary system. Perryman et al. (1998) used the absolute trigonometric parallaxes from the *Hipparcos* Catalogue to determine individual distances to members of the Hyades and concluded that 91 Tau is not a member of the Hyades cluster. Abt & Morrell (1995) measured the projected rotational velocity as $v \sin i = 53\,\mathrm{km\,s^{-1}}$, but scaling this value to the results of Royer et al. (2002) changes the velocity to $v \sin i = 63\,\mathrm{km\,s^{-1}}$. According to Abt & Levy (1985), HD 29479 is an A2 star based on the Ca II K-line and an A7 based on the metallic and hydrogen lines. These authors also derived the following orbital elements: $P_{\mathrm{orb}} = 38.951^d$, $e = 0.15$, $K = 7.9\,\mathrm{km\,s^{-1}}$, $V_0 = 26.1\,\mathrm{km\,s^{-1}}$ and $\omega = 82\overset{\circ}{.}0$.

The star has broad lines. We were only able to put an upper constraint on the abundances of Li, C, Al. Sulphur and oxygen seem normal but oxygen is rather uncertain. Carbon and calcium are underabundant and most of the other elements like Si, Ti, Fe, Ba are overabundant. This is a typical Am star pattern, which corresponds well to the rotation and orbital elements of the star. Our value of the projected rotation velocity is intermediate between that of Abt & Morrell (1995) and Royer et al. (2002). We would like to point out that one of our radial velocity measurements ($-1.3\,\mathrm{km\,s^{-1}}$) does not fit into the predicted radial velocity curve which spans roughly the region from 18 to 34 $\mathrm{km\,s^{-1}}$ (see Fig. 4), and that the orbital elements need to be revised.

4.5 HD 96528

HD 96528 (64 Leo, HR 4322, BD+24 2318, HIP 54388, SAO 81681, A5m) is a spectroscopic binary system (Adams 1915). Heard (1937) obtained the period $P_{\mathrm{orb}} = 40.45^d$. Later, Lucy & Sweeney (1971) published the following orbital elements: $e = 0.08$, $K = 17.6\,\mathrm{km\,s^{-1}}$, $V_0 = -3.4\,\mathrm{km\,s^{-1}}$ and $\omega = 308\overset{\circ}{.}0$. The projected rotational velocity measured by Abt & Morrell (1995) was $v \sin i = 85\,\mathrm{km\,s^{-1}}$. However, if these measurements were scaled to the results of Royer et al. (2002), the latter authors predict $v \sin i = 96\,\mathrm{km\,s^{-1}}$.

The stellar lines are very broad and blended. It is very difficult to observe weak lines and estimate the microturbulence, which complicates the abundance analysis, and thus the abundances are only approximate. Nevertheless, the star is deficient in C and Ca with overabundances in Al, Ti and Ba. We conclude that this is a mild Am star. [Ca/Fe] = -0.53 which is not so sensitive to the uncertainties in the temperature and microturbulence confirms that this is a genuine broad-lined Am star. Our rotational velocity ($v \sin i = 85\,\mathrm{km\,s^{-1}}$) corresponds well to the value of Abt & Morrell (1995). This is probably the Am binary with the highest rotational velocity among Am binaries with the orbital periods in the range 20–200 d, and its velocity even exceeds the limit of 75 $\mathrm{km\,s^{-1}}$ found by Budaj (1996) for these orbital periods and pushes the limit to higher values. It certainly does not have synchronous rotation, and its mild peculiarity corresponds to what one could expect for its fast rotation and low eccentricity. The above mentioned radial velocity curve of Heard (1937) or Lucy & Sweeney (1971) varies from about –19 to $+17\,\mathrm{km\,s^{-1}}$. We point out that both of our radial velocity measurements do not agree with the predicted radial velocity curve of HD 96528 (see Fig. 4); however, this disagreement could still be understood by a possible uncertainty in the phase accumulated over the time and uncertainties in the radial velocity measurements.

4.6 HD 108651

HD 108651 (HR 4751, Tr 145, BD +26 2353, HIP 60891, SAO 82328, Am) is a well-known and well-studied Am binary. A number of authors have worked on its chemical composition: Burkhart & Coupry (2000), Iliev et al. (1998), Savanov (1996) and Boesgaard (1987). In general, they found the abundance pattern with medium overabundances of rare Earth elements and a low Ca/Fe ratio – an indicator of the pronounced Am characteristics. As far as the projected rotational velocity is concerned, various values can be found in the literature. Bernacca & Perinotto (1971) obtained 6 $\mathrm{km\,s^{-1}}$, while Uesugi & Fukuda (1982) and Kraft (1965) list 12 $\mathrm{km\,s^{-1}}$. Savanov (1996) and Iliev et al. (1998) found a value of 20 $\mathrm{km\,s^{-1}}$ which is in good agreement with Abt & Willmart (1999) who indicated 22 $\mathrm{km\,s^{-1}}$. The latter authors computed the orbital elements of the star: $P_{\mathrm{orb}} = 68.290^d$, $e = 0.296$, $K = 14.0\,\mathrm{km\,s^{-1}}$, $V_0 = -1.8\,\mathrm{km\,s^{-1}}$ and $\omega = 260\overset{\circ}{.}7$.

HD 108651 has the sharpest lines of the six stars studied in this work. Lithium is clearly detected and is normal. Carbon, oxygen and calcium are underabundant, but only fair upper limits could be estimated for C, O and their real abundances are probably much lower. Aluminium and sulphur seem quite normal while Ti, Fe, Ni,

Table 4. Chemical abundances of HD 108651 as taken from Boesgaard (1987), Savanov (1996), Iliev et al. (1998) and Burkhart & Coupry (2000). All values are in [N/H] scale.

	B87	S96	I98	BC00	This paper
Li	+1.85		+1.98	+1.85	+2.01
C		−0.19	−0.32		⩽−0.44
Al		−0.66	−0.81		+0.16
Si		+0.34	+0.53		+0.22
Ca		−0.25	−0.37		−0.52
Ti		+0.12	−0.01		+0.28
Fe	+0.32	+0.24	+0.36	+0.40	+0.45
Ni		+0.59	+0.90		≈+0.71

Ba are overabundant. A comparison with the previously derived atmospheric abundances is given in Table 4. The agreement with the abundances of other authors is quite good except that of Al abundance. In Paper I, Budaj & Iliev have already pointed out that some earlier Al and Si abundances derived from Al I 6696 Å and Si I 6722 Å might be very uncertain (especially Al could have been considerably underabundant) due to the imprecise gf-values and silicon blends of Al lines.

This is a very pronounced strong Am star. Its projected rotation velocity is low, while it also has the highest eccentricity of the six stars. One would expect the strongest peculiarity in agreement with the observations. Finally, we can conclude that our radial velocity measurements are in agreement with the recent orbit of Abt & Willmart (1999) (see Fig. 4).

5 CONCLUDING REMARKS

In this second paper, we have analysed another six binaries from our sample and derived their chemical composition, temperatures, gravities, projected rotational velocities, masses and ages. We concluded that HD 861, 29479 and 108651 are typical Am stars, HD 20320 and 96528 are mild Am stars, while HD 18778 is not an Am star, although its projected rotational velocity was very low. On the contrary, HD 96528 has one of the highest projected rotational velocities among Am binaries with orbital periods in the range 20–200 d but still exhibits Am anomalies. Feňovčík et al. (2004) performed a preliminary statistical analysis of the stars analysed here and in Paper I, and found a nice correlation of [Ca/Fe] with $v \sin i$, eccentricity and some other more subtle effects. However, because the rotation of Am stars in binary systems is strongly correlated with the orbital period and eccentricity due to the synchronization and circularization effects, the question about the true origin of the above mentioned correlations remains. Is the correlation of Am peculiarity with the rotation a pure manifestation of its dependence on orbital elements or vice versa? Such studies of Am binaries in a multidimensional space of parameters are thus very important. They can help us to understand poorly studied processes that are related to stellar rotation, evolution and tidal effects, which can operate in all binary stars and could leave observable imprints in Am binaries.

When the projected rotational velocities are compared with the theoretical pseudo-synchronization velocity (see table 1 of Budaj 1997a), we found that all primary components of binary systems studied in this work do not rotate synchronously and also rotate faster than the pseudo-synchronization velocity. This means that the pseudo-synchronization is not a necessary condition for the appearance of the Am phenomenon. This is, however, based on the assumption that the spin and orbit axes are parallel and that the orbital elements are correct. However, we also realized that at least in one case (HD 29749) out of six stars in this sample the orbital elements are either not very precise or variable. It does not mean that many orbital periods or eccentricities which are most important for our study are wrong. There could be a third body in a system which would affect mainly the gamma velocity which is not relevant for our study. However, as pointed out by Iliev et al. (2001a,b), Budaj et al. (2004) and Paper I, this is only the tip of the iceberg and there are many cases when older photographic data were misinterpreted because of the presence of an unresolved companion. Thus, new CCD spectroscopic observations of even nearby and bright Am binaries with known parallaxes or distances are encouraged. This would provide valuable information on abundances, orbital elements, masses and ages of these stars, lead to a discovery of secondary spectra in many SB1 systems, provide the measurements of mass ratio and, ultimately, shed more light on the role of tidal effects in Am/Ap phenomena and the interior magnetohydrodynamics of binary stars.

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