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Abundance analysis of Am binaries and search for tidally driven abundance anomalies – I. HD 33254, HD 178449 and HD 198391

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ABSTRACT

It is suggested that if the tidally induced meridional circulation of Tassoul & Tassoul existed, it might successfully compete with diffusion processes and rotationally induced meridional circulation. This could affect the chemical composition of an Am binary component. The main goal of this paper is to start a systematic abundance analysis of a sample of Am binaries in order to search for possible observable abundance anomalies driven by tidal interaction in these binary systems.

A synthetic spectrum analysis of CCD observations in two spectral regions (6400–6500 and 6660–6760 Å) of HD 33254, HD 178449 and HD 198391 was carried out. Basic stellar properties, atmospheric parameters and abundance patterns were derived. HD 33254 is the star with pronounced Am anomalies, while HD 198391 is found to be an extremely sharp-lined hot Am star. HD 178449 is a controversial and extremely highly rotating star. We have succeeded in detecting a very faint secondary spectrum. The most probable explanation is that we have discovered the new spectroscopic Ab component of this spectroscopic and visual multiple system.

Key words: diffusion – binaries: close – stars: chemically peculiar – stars: individual: HD 33254 – stars: individual: HD 178449 – stars: individual: HD 198391.

1 INTRODUCTION

Am stars are 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. This peculiarity seems to be due to microscopic selective diffusion driven mainly by radiation pressure and gravity. The diffusion operates first below the deepest He II convection zone until it disappears because of He settling and then proceeds much higher and more effectively below the H+He I convection zone. An additional superficial iron convection zone may develop on the MS (Michaud 1970; Richard, Michaud & Richer 2001). Rotation was found to play a key role in this process as it induces large-scale mixing which can disturb the slow diffusion process. Most elaborated calculations by Charbonneau & Michaud (1991) indicate that a rotational velocity less than about 90 km s^{-1} is required for diffusion to prevail and for the Am phenomenon to occur. There is a growing amount of recent observational evidence supporting the above-mentioned picture, revealing that either a smooth or a step function dependence of Am peculiarity on rotation exists (Abt 2000; Burkhart & Coupry 2000; Varenne & Monier 1999; Takeda & Sadakane 1997; Abt & Morrell 1995; Savanov 1995). Abt and Abt & Morrell even favour the view that 'rotation alone can explain the appearance of an A star as either abnormal or normal.' Nevertheless, Am peculiarity does seem to depend on evolutionary status or age as well. (1) It may 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 (2) observable abundances of some elements may significantly depend on age (Alecian 1996). Apart from this, the Am phenomenon is apparently restricted to a well-defined region of the MS in the Hertzsprung–Russell diagram (HRD) which further involves its dependence on atmospheric parameters such as effective temperature and gravity (Künzli & North 1998; Hui-Bon-Hoa 2000). However, it is usually difficult to distinguish evolution and temperature effects as temperature and age strongly correlate. Recent findings of Domingo & Figueras (1999) state that there is no significant difference between the evolutionary status of Am and normal A-type stars while Künzli & North found a deficit of young Am stars.

There are also indications that Am peculiarity may depend on the orbital elements in a binary system (Budaj 1996, 1997; Iliev et al.

⋆http://www.ta3.sk/∼budaj

1998). It seems more pronounced in eccentric orbits and possibly also at longer orbital periods provided that the binary components are relatively close (orbital periods $P_{\rm orb} < 180$ d). Because Am stars are often found in binaries (Abt 1961, 1965; Abt & Bidelman 1969; North et al. 1998; Debernardi et al. 2000) they offer us a unique chance to study the influence of a companion on the stellar hydrodynamics. It will be the main aim of this paper to start a systematic spectroscopic investigation of Am binaries and to concentrate also on the possible dependence of Am peculiarity on the orbital elements. Let us start with an idea of what we will be looking for or expecting from the observations. This is introduced in Section 2. How we will do this is described in Sections 3 and 4, and first results are presented in Section 5.

2 MOTIVATION

Tidal effects might play a unique role in driving CP phenomenon. The stellar companion induces additional large-scale motions, flows, oscillations – inside and/or on the surface of the star which may mix the medium. We will refer to these processes as tidal mixing. On the other hand, tidal effects may also act as a stabilizing agent suppressing other mixing processes (e.g. rotationally induced mixing), evidence of which is that some late-type tidally locked binaries possess higher Li surface abundances (Ryan & Deliyannis 1995). One of us (Budaj 1996) has suggested an empirical 'tidal mixing + stabilization' hypothesis to account for the behaviour of some of the previously mentioned observations in Am stars. The question arises whether these hypothetical processes can find a more physical footing among the known theoretical processes operating in binary stars. Theoretical analysis of tidal effects is concerned with mainly synchronization and circularization mechanisms. There are two competing but not mutually exclusive (Tassoul 1995) views of this problem in early-type binaries.

In the dynamical tide theory of Zahn (1977) a variety of gravity modes (g-modes) are induced by the tidal potential mainly if eccentric orbits are involved. He has shown that in stars with radiative envelopes radiative damping retards the dynamical tide which results in spin–orbit synchronization and circularization. The theory predicts that synchronization prevails within orbital periods of about 2 d and circularization within about 1 d for an A-type binary. An observational search for forced oscillations in early-type binaries is under way by Harmanec et al. (1997). Recently, Eggleton, Kiseleva & Hut (1998) suggested that turbulent viscosity dissipation acting on the equilibrium tide can also operate on the upper MS. This mechanism was originally proposed by Zahn (1977) for stars with convective envelopes. It assumes that the star is in hydrostatic equilibrium and non-zero viscosity causes tidal bulge to lag (or to lead) the secondary star. This induces tidal torque and subsequent spin–orbit synchronization and circularization.

In the hydrodynamical mechanism of Tassoul & Tassoul (1992) the lack of axial symmetry in a non-synchronously rotating tidally distorted star produces large-scale meridional currents via Ekman pumping. These currents exchange mass and angular momentum. This mechanism can remain operative for larger orbital periods, up to $P_{\rm orb} \approx 100$ d, without bringing complete pseudo-synchronization beyond $P_{\rm orb} \approx 15$–25 d; also, as far as circularization is concerned, up to $P_{\rm orb} \approx 10$ d. The geometry of such currents is similar to rotationally induced meridional circulation in the sense that they rise (sink) at the equator and sink (rise) at the poles if the rotational period is shorter (longer) than the orbital one. In the following we will take a closer look at this mechanism.

The typical speed of such currents is of the order of

$$u \approx \epsilon_{\rm T} \frac{\delta}{R} (\omega_{\rm i} - \omega_{\rm o}) R^* = 2\pi \epsilon_{\rm T} \frac{\delta}{R} \left(\frac{1}{P_{\rm rot}} - \frac{1}{P_{\rm orb}} \right) R^* \quad (1)$$

where R is the stellar radius, R^* is the distance from the rotational axes, $\omega_{\rm i}$ is the initial rotation angular velocity, $\omega_{\rm o}$ is the orbital angular velocity and $P_{\rm rot}$ is the rotational period. $\epsilon_{\rm T}$ is the ratio of tidal to gravitational forces at the equator

$$\epsilon_{\rm T} = \frac{M'}{M} \left(\frac{R}{d} \right)^3 \quad (2)$$

where M and M' are the masses of the star and its companion, respectively, and d is the separation between the stars. δ is the thickness of the Ekman-type boundary layer

$$\frac{\delta}{R} = 3 \times 10^{-5+N/4} (P_{\rm orb})^{1/4} \left(\frac{L/{\rm L}_\odot}{M/{\rm M}_\odot} \right)^{1/4} \quad (3)$$

where N is a parameter equal to $\approx$0 in a radiative envelope and $\approx$10 in a convective envelope, L, ${\rm L}_\odot$, M, ${\rm M}_\odot$ are the luminosity and mass of the star and Sun, respectively. The above results were obtained by the authors under several simplifying assumptions and we have to be aware of the limitations of the theory; for example, Tassoul & Tassoul (1992) considered a model with constant density, $M'/M \approx 1$, circular orbit and $|\omega_{\rm i} - \omega_{\rm o}| \ll \omega_{\rm o}$. Our choice of $N = 0$ will be something like a lower limit but, on the other hand, such currents may be hampered by other effects and Claret, Giménez & Cunha (1995) found that observed synchronization times are 1.6 dex longer than expected.

Now, we recall the pioneering paper of Michaud (1982) where he studied the competition between rotationally induced mixing and helium settlement by diffusion. He compared the downward diffusion velocity of helium at a point about one pressure scaleheight below the He II superficial convection zone (multiplied by a factor of 10) with a typical speed of the rotationally induced meridional circulation after Tassoul & Tassoul (1982). What he found was that for HgMn stars with equatorial rotation exceeding some critical value, $V_{\rm rot} > 90$ km s^{-1}, meridional circulation will prevail over diffusion and stars will sustain their superficial convection zones. This is now a generally accepted explanation – a reason for the slow rotational velocities of CP stars. The typical speed of rotationally induced meridional circulation is of the order of

$$u = 5 \times 10^{-16} u(r, 0) \frac{R/{\rm R}_\odot}{M/{\rm M}_\odot} v_{\rm rot}^2, \quad (4)$$

where $u(r, 0)$ is a function of depth tabulated in Tassoul & Tassoul (1982) but we have simply assumed $u(r, 0) \approx 10^{-2}$ cm s^{-1} which is an upper limit. We have also followed the steps of Michaud and estimated the helium diffusion velocity one pressure scaleheight under the He II superficial convection zone. The CESAM stellar model of a $M = 2\,{\rm M}_\odot$, 0.54×10^9 yr old star with solar chemical composition and 0.3H overshooting of Morel (1997) was used for this purpose along with the DIF4 code of Budaj & Dworetsky (2002) for the He settling diffusion velocity calculations. The radiative acceleration on helium was neglected in the latter.

The behaviour of these typical velocities (equations 1 and 4 and the He diffusion velocity) is depicted in Fig. 1. We can split the whole region of orbital periods into three areas. For sufficiently short orbital periods ($P_{\rm orb} < 4$ d, figure 2 of Budaj 1996) synchronization is very strong and the assumption of Tassoul & Tassoul, $|\omega_{\rm i} - \omega_{\rm o}| \ll \omega_{\rm o}$, is fulfilled. Unfortunately, it is hard to derive from observation the exact degree of synchronization because of the inclination uncertainty in $v \sin i$ (it might be possible, for example, in

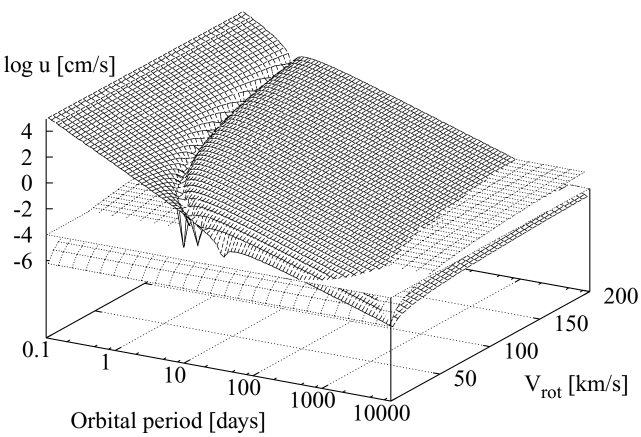

Figure 1. Typical velocity of tidally induced currents (dense surface) in the $P_{\rm orb} \times v_{\rm rot}$ plane estimated for $M = 2\ \mathrm{M}_{\odot}$, $M' = 1\ \mathrm{M}_{\odot}$, $R = 2\ \mathrm{R}_{\odot}$, $L = 17\ \mathrm{L}_{\odot}$, $N = 0$ versus that of typical rotationally induced currents (rare surface) and that of downward helium diffusion (plane) one pressure scaleheight below the He II superficial convection zone multiplied by a factor of 10.

Ap stars where rotational periods are known). In the intermediate region of orbital periods ($4 < P_{\rm orb} < 30$ d, table 1 of Budaj 1997) pseudo-synchronization can still occur and $|\omega_{\rm i} - \omega_{\rm o}| \approx \omega_{\rm o}$. Here, the tidal currents are predicted to be at least 3 dex larger than rotational ones. This is a large difference that would not be fully compatible with helium settling and the Am phenomenon, and some effect reducing the speed of the theoretical tidal currents by a few dex might be required. For still longer orbital periods, the assumption of Tassoul & Tassoul is not fulfilled and no safe conclusions can be drawn about their mechanism. Nevertheless, we could expect from Fig. 1 and equation (1) that generally Am peculiarity should become more pronounced when approaching the apparent dip (caused by the synchronization) or larger orbital periods. Note also that it should cease towards higher rotation. Consequently, the observed dependence of Am peculiarity on rotation in binaries cannot be used as an argument for rotationally induced mixing, as tidal effects are also expected to have the same effect. We could also expect a qualitative break in the hydrodynamics at some orbital period where rotationally induced currents overwhelm tidally induced ones. Although the above picture should be viewed as an order of magnitude analysis and more elaborate hydrodynamical simulations are required for firmer conclusions, it seems that tidally induced currents may successfully compete with rotationally induced currents and thus also with the diffusion process.

3 OBSERVATIONS AND SAMPLE STARS

We searched the area of 5000–9000 Å for weak but still detectable unblended lines of most peculiar elements such as Ca, Sc, Mg, C, etc. We decided to observe each star in two spectral regions, 6400–6500 Å (Ca) and 6660–6760 Å (Li), and to focus on Ca I 6439 and the rich spectrum of iron lines. Additional observations in the special case of HD 178449 were made in the region 3880–3950 Å (Ti).

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 observational programme on Am stars in binary systems. 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 typical $R = 32\,000$ and a signal-to-noise (S/N) ratio of about 300. The instrumental profile was checked and adjusted during each set-up of instruments using the comparison line spectrum so that its FWHM was about 0.2 Å and never exceeded this value. The IRAF standard procedures were used for bias subtracting, flat-fielding and wavelength calibration. Telluric lines were removed using spectra of hot, fast rotating stars. Wavelength calibration has the rms error of 0.005 Å. The EQWREC2 code of Budaj & Komžík (2000) was also used for some tasks such as continuum rectification, radial velocity and equivalent width measurements. The log of observations relevant to this paper is listed in Table 1.

Table 1. Log of observations: spectrum number, date (yyyy.mm.dd), HJD (2450000+) of the beginning of the exposure, effective exposure time (min), spectral region, heliocentric radial velocity of the primary and the secondary spectrum (km s^{-1}).

No.	Date	HJD	Exp.	Reg.	RV1	RV2
		HD 33254				
1	2001.11.01	2214.530	20	Li	+43.8	
2	2001.12.22	2266.417	45	Ca	+44.5	
		HD 198391				
1	2001.06.11	2072.477	115	Li	−7.8	
2	2001.08.30	2152.324	70	Ca	−7.8	
		HD 178449				
1	2000.07.22	1748.371	20	Ca	−10.4	−16.8
2	2001.03.05	1973.603	45	Ca	−13.7	−19.0
3	2001.04.03	2003.499	170	Ca	−15.4	−19.3
4	2001.08.30	2152.235	120	Ca	−13.8	−17.0
5	2002.05.18	2412.503	60	Ca	−10.3	−18.8
6	2000.07.22	1748.421	25	Li		
7	2002.05.17	2412.452	60	Ti		

A few tens of Am binaries from the sample of Budaj (1996) were chosen so that they satisfy the following criteria: targets brighter than the seventh magnitude in the V filter with declination $\delta > -10$ deg. Only stars with orbital periods $10 < P_{\rm orb} < 180$ d will be considered for the beginning. This ensures a full range of original eccentricities which did not undergo circularization on the MS. We put no constraint on the rotational velocity and included one more broad-line normal star for testing the analysis on highly rotating stars. It will be the subject of this paper to start with an analysis of the three most different stars in the sample and calibrations on the Sun: namely, a hot Am extremely sharp-lined star HD 198391, a pronounced Am star HD 33254 and a cool highly rotating normal star HD 178449.

4 ATMOSPHERIC PARAMETERS AND SPECTRUM SYNTHESIS

In Table 2 we summarize relevant information about our programme stars. The $uvby\beta$ indices (de-reddened by using the UVBYBETA code of Moon & Dworetsky 1985) are from Renson (1991). Geneva and *UBV* photometry are from Rufener (1980) and Mermilliod, Mermilliod & Hauck (1997), respectively. Parallaxes are from the *Hipparcos* mission (ESA 1997). The atmospheric parameters were derived using the TEFFLOGG code of Moon & Dworetsky (1985) (Smalley & Dworetsky 1995 were also consulted) from $uvby\beta$ photometry and using the Kobi & North (1990) calibration of Geneva photometry. If both estimates were available, we accepted their rounded mean as the best choice for model atmosphere parameters. All these stars (except possibly HD 178449) seem to be SB1

Table 2. Photometry, atmospheric parameters and other relevant information about the observed stars. Note that 'oog' denotes 'out of grid', $T_{\rm eff}$ is in Kelvin, log g is in CGS units, $P_{\rm orb}$ is in d and π is in mas.

Star	HD 33254	HD 198391	HD 178449
V	5.424	6.325	5.211
B–V	0.247	0.020	0.351
U–B	0.167	−0.020	0.044
$E(b$–$y)$	0.005	0.012	0.023
$(b$–$y)_0$	0.133	−0.005	0.230
m_0	0.247	0.157	0.151
c_0	0.839	1.075	0.704
β	2.823	2.878	2.702
$T_{\rm eff}$	7920	9650	6790
log g	4.20	3.89	3.57
$B2$–$V1$	0.028	−0.137	–
d	1.206	1.511	–
$T_{\rm eff}$	7741	oog	–
log g	4.06	oog	–
	Adopted parameters		
$T_{\rm eff}$	7830	9650	6790
log g	4.13	3.89	3.57
$P_{\rm orb}$	155.83[a]	10.883[b]	42.857[c]
e	0.67[a]	0.39[b]	0.0[c]
π	18.54 ± 0.83	6.30 ± 0.84	24.64 ± 0.54

Notes: [a]Conti (1969); [b]Shajn (1933); [c]Dworetsky (1983).

Table 3. List of lines with their gf-values corrected.

Line	Wavelength (Å)	Old gf	New gf
Ni I	6414.581	−1.180	−1.3
Si I	6414.980	−1.100	−1.17
Fe I	6416.929	−0.885	Should be lower
Co I	6417.778	−1.318	−1.9
Si I	6440.566	−2.480	−2.9
Mn I	6440.971	−1.238	−1.4
Si I	6442.777	−1.240	Removed
Fe II	6442.955	−2.885	−2.6
Ca I	6449.808	−1.015	−0.4
Co I	6450.247	−1.698	−2.1
Si I	6451.517	−1.390	−2.5
Co I	6454.990	−0.250	−0.5
Ca I	6455.598	−1.557	−1.37
Fe II	6456.383	−2.100	−2.082
Ca II	6456.875	−0.426	−0.03
Ca II	6456.875	−0.539	−0.03
Si I	6460.909	−1.830	−2.4
Si I	6461.074	−1.900	−2.6
Fe I	6464.661	−5.201	−5.5
Fe I	6465.759	−1.571	Removed
Si I	6467.002	−1.520	−2.1
Si I	6467.308	−1.870	−2.4
Fe II	6482.204	−2.268	−1.8
Ni I	6482.796	−2.630	−2.95
Ti II	6491.561	−1.793	−2.10
Fe I	6494.526	−1.869	−1.3
Fe I	6663.231	−1.126	−1.35
Si I	6665.189	−1.560	−2.0
Ti II	6680.133	−1.855	−2.15
Fe I	6687.490	−2.323	−2.8
Ca I	6691.021	−0.416	−1.0
Al I	6696.023	−1.347	−1.65
Al I	6696.788	−1.421	−1.65
Al I	6698.673	−1.647	−1.95
Ti I	6706.288	−1.58	Removed
Ni I	6711.575	−3.807	−4.5
Si I	6721.848	−1.49	−1.15
Fe I	6724.082	−1.521	Removed
Fe I	6726.661	−0.829	−1.05
Si I	6735.037	−2.010	−2.5
Si I	6739.493	−1.860	−2.4? blended
Ti I	6743.122	−1.630	−1.8
Si I	6747.435	−2.110	−2.5
Si I	6759.347	−2.180	−2.7
Si I	6762.180	−1.810	−2.4

binaries, 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 (1993). The Vienna Atomic Line Data Base (VALD; Kupka et al. 1999) also containing Kurucz (1990) 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 we tried to reproduce the Spectral Atlas of Solar Absolute Disc-Averaged Intensity (Neckel 1999) spectrum and to calibrate gf-values of those lines which did not match. For the solar photosphere we used a model with $T_{\rm eff} = 5777$ K, log $g = 4.438$ and the value of microturbulence $\xi = 1$ km s^{-1} (Bellot Rubio & Borrero 2002). In Table 3 there is a list of our new and old gf-values which were corrected or questioned in this way. The gf-values of Ca I 6455.6 and Fe II 6456.4 were taken from Koza (private communication). It turned out, for example, that some previous Al and Si abundances or [Al/Si] derived from Al I 6696.0 and Si I 6721.8 are very uncertain as these lines have an opposite gf-value correction and, moreover, the Al line is blended by Si. Our gf-values for these two lines are close to those obtained by Burkhart & Coupry (2000).

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

5 RESULTS

The equivalent widths of some selected lines were measured and are listed in Table 4. The abundances obtained by synthetic spectrum fitting analysis are introduced in terms of $[{\rm N/H}] = \log({\rm N/H})_\star - \log({\rm N/H})_\odot$ in Table 5. 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, occurring mainly in weak blends, are only approximate. The abundances of Ba should be taken with caution as they are usually derived from only one line Ba II 6497 at the edge of our frames. Apart from abundances and atmospheric parameters, we also derived the basic stellar properties. All stars are bright and reliable parallaxes are known from the *Hipparcos* mission. We have benefited from that and interpolated in the evolutionary tracks and isochrones of Lejeune & Schaerer (2001). The masses, ages and expected terminal age MS obtained are also listed in Table 5 and the position of our programme stars in HRD is illustrated in Fig. 2. Radial velocities, projected rotational velocities and microturbulent velocities were also determined as a by-product. A discussion of individual stars follows.

Table 4. Equivalent widths of selected lines in mÅ. Some of the lines occurred in blends and the equivalent width of the whole blend was measured and ascribed to the position of the normally most pronounced component. We tried to avoid ambiguities in the notes below.

Line	Wave. [Å]	HD 33254	HD 198391	HD 178449
Ca II	3933.663	–	–	5175.8
Fe I	6400.001	133.9	16.4	102.4
Fe II	6407.251	43.9	9.3	–
Fe I	6408.018	72.5	4.6	–
Fe I	6411.649	97.8	9.9	–
Fe II	6416.919	104.9	42.2	–
Fe I	6419.950	75.7	10.1	–
Fe I	6421.351	94.2	3.9	–
Fe I	6430.846	82.4	3.2	125.8^{f}
Fe II	6432.680	98.5	33.2	–
Fe II	6433.814	16.0	6.6	–
Ca I	6439.075	73.1	12.4	156.3
Fe II	6442.955	24.4	10.7	–
Fe II	6446.410	34.4	16.2	–
Ca I	6449.808	30.9	–	103.5
O I	6453.606	–	7.0	–
O I	6454.446	–	15.2	–
Fe II^{a}	6456.383	224.2	143.1	197.6
Ca I	6462.567	88.3	9.7	157.5
Fe I	6469.193	40.7	–	–
Ca I	6471.662	–	–	86.9
Fe II	6482.204	87.1	23.2	34.7^{g}
Ni II	6484.083	11.9	–	–
Fe II	6487.339	4.9	–	–
Ti II^{b}	6491.561	51.7	17.4	–
Fe II	6493.035	20.5	11.8	–
Ca I	6493.781	17.0	6.3	–
Fe I	6494.980	127.2	14.0	–
Ba II	6496.897	267.4	33.3	453.8^{h}
Fe II	6677.305	–	10.4	–
Fe I	6677.987	113.5^{d}	14.2^{c}	88.1^{i}
Ti II	6680.133	13.9	–	–
Al I	6696.023	19.3	–	–
Fe I	6705.101	23.4	–	–
Li I	6707.	–	–	54.1
Fe I	6713.046	11.5	–	–
Fe I	6713.745	8.4	–	–
Fe I	6715.383	10.5	–	–
Ca I^{e}	6717.681	27.7	4.1	75.9
Si I	6721.848	27.6	–	–
Fe I	6726.661	26.6	–	–
Fe I	6733.151	7.6	–	–
Si I	6741.628	14.1	–	–
S I	6743.531	43.2	6.5	–
S I	6748.837	71.7	13.9	–
Fe I	6750.153	25.5	–	–
Fe I	6752.707	20.6	–	–
S I	6757.171	68.3	17.1	–

Notes: ^{a}Fe II + O I + Ca II; ^{b}Fe II + Ti II; ^{c}He I + Fe I; ^{d}Fe I + Fe II 6677.305; ^{e}Ti II + Ca I; ^{f}Fe I + Fe II; ^{g}Fe I + Ni I + Fe II; ^{h}Ba II + Fe I + Ca I + Ti II; ^{i}Fe I + Ti II.

5.1 HD 33254

The star HD 33254 (16 Ori, HR 1672, BD+09 743, HIP 23983, SAO 112467, CCDM J05093+0949A, A2m) is a well-known Am and spectroscopic binary star. It is the A component of IDS 05038+0942. Component B is a 12.2-mag star, observed 88 arcsec away from A. The spectral type of HD 33254 is described as A2/A7/F2 (III–IV) (from Ca II K, hydrogen and metal lines, respectively) by Gray & Garrison (1989). The projected rotational velocity measured by Abt & Morrell (1995) is $v \sin i = 13$ km s^{-1}. However, if their measurements are scaled to fit the results of Royer et al. (2002), the latter authors predict $v \sin i = 21$ km s^{-1}. It is a member of the Hyades cluster. Conti (1970) pointed out that this star had the most extreme Am abundance anomalies and Burkhart & Coupry (1989) discovered that, compared to other Am stars, it is also extremely deficient in lithium.

Table 5. Abundances derived in terms of [N/H] for our three stars. Abundances of the Sun are in terms of $\log(N_{\rm el}/N_{\rm H}) + 12.00$.

	Sun	HD 33254	HD 198391	HD 178449
He	11.00		0.00	
Li	1.10	$\leqslant$+1.68	$\leqslant$+2.20	+2.08
C	8.52	$\leqslant$−0.74	$\leqslant$−0.12	
N	7.92		$\leqslant$+0.13	
O	8.83	$\leqslant$−0.23	−0.15	
Ne	8.08		$\leqslant$−0.23	
Al	6.47	+0.31		
Si	7.55	+0.35		
S	7.33	+0.13	+0.26	
Ca	6.36	−0.68	+0.07	−0.02
Ti	5.02	+0.26		
Fe	7.50	+0.52	+0.33	−0.40
Ni	6.25	≈+0.90		
Ba	2.21	+1.90	+1.30	≈+0.19
Eu	0.54	$\leqslant$+1.16	$\leqslant$+1.76	
$\xi_{\rm turb}$		2.7	0.8	2.5
$v \sin i$		13	$\leqslant$6	139
M		1.86	2.65	1.67/0.8
log T		8.91	8.57	9.17
log *TAMS*		9.15	8.70	9.28

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

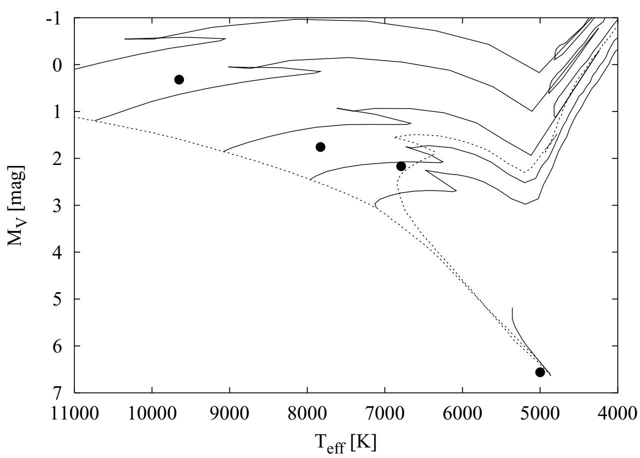

Figure 2. HRD for our three programme stars. The star at the bottom is a possible Ab component of HD 178449. Evolutionary tracks for $M = 3.0$, 2.5, 2.0, 1.7, 1.5 and 0.8 $M_{\odot}$ are shown solid, isochrones for $\log T = 3.0$ and 9.19 yr are shown dotted (Lejeune & Schaerer 2001).

The spectrum of this star is typical for an Am star. For some elements we were able to determine only upper limits (Li, C, O, Eu). The abundance of Ni is quite large but it is highly uncertain as its lines appear only in weak blends. Barium seems most

Table 6. HD 33254: a comparison of abundances obtained by different authors in terms of [N/H].

	TS97	HA98	BC89	BI03
Li			+1.20	⩽+1.68
O	−0.95			⩽−0.23
Al			+0.43	+0.31
Si			+0.35	+0.35
Ca		−0.58	−0.31	−0.68
Fe	+0.25	+0.45	+0.75	+0.52
Ni		+0.90		≈+0.90
ξ_{turb}	5.3	3	3	2.7
$v \sin i$	12	16		13

Notes: TS97 – Takeda & Sadakane (1997); HA98 – Hui-Bon-Hoa & Alecian (1998); BC89 – Burkhart & Coupry (1989); BI03 – this paper; ξ_{turb}, $v \sin i$ are in km s^{-1}.

peculiar and overabundant by about 2 dex. The upper limit for Eu is estimated from the Eu III 6666 gf-value of this line (1.18), which was taken from Ryabchikova et al. (1999). The star does not seem to have a very strong Eu overabundance. In the spectra of a few Am stars including this one we detected an unexpected line at 6438 Å which is probably Eu II 6438 blended with Si I. Carbon and calcium are in a large deficit. We can claim that oxygen and lithium have at least a mild deficit, but it is known that these elements are highly underabundant also (see Table 6 and references therein). Al, Si, S, Ti and Fe are all slightly overabundant with iron being the most peculiar. The rotation is in perfect agreement with Abt & Morrell (1995) but the scaling of Royer et al. (2002) does not work for this star. Its microturbulence of 2.7 km s^{-1} is compatible with values encountered in such stars. As an illustration we depict part of the spectra of HD 33254 and HD 198391 and their spectrum synthesis in Figs 3 and 4. The abundances of some elements were also derived by Burkhart & Coupry (1989), Takeda & Sadakane (1997) and Hui-Bon-Hoa & Alecian (1998) and we can compare and test our results (see Table 6). There are sometimes large differences between the different authors. Our abundances of Li, Al and Si and microturbulence are in good agreement with Burkhart & Coupry while the abundances of Ca, Fe and Ni are in better agreement with Hui-Bon-Hoa & Alecian. Our rotation velocity is almost the same as that determined by Takeda & Sadakane (1997).

5.2 HD 198391

The star HD 198391 (14 Del, HR 7974, BD+07 4556, HIP 102819, SAO 126265, A1 Vs) is a spectroscopic binary star. Its orbit was published by Shajn (1933). Abt & Bidelman (1969) and Abt & Morrell (1995) classified the star as A1 V and A1.5 IV, respectively. The projected rotational velocity derived by Abt & Morrell (1995) is $v \sin i = 15$ km s^{-1}. However, if their measurements are scaled to fit the results of Royer et al. (2002) the latter authors predict $v \sin i = 23$ km s^{-1}.

This is apparently a much hotter star with fewer but extremely sharp lines. We would like to note that both our spectra have radial velocity slightly higher than predicted by the radial velocity curve of Shajn (1933) ($K = 31.4$ km s^{-1}, $V_0 = -30.2$ km s^{-1}). It has a very low projected rotational velocity and the lines are widened mainly by the instrumental profile. It can be easily compared with HD 33254 in Fig. 3. Consequently, Abt & Morrell overestimated its rotation and the scaling of Royer et al. does not work well in such a case. We can safely put only an upper limit of about 6 km s^{-1} but we used a value of 4 km s^{-1} in our calculations. It

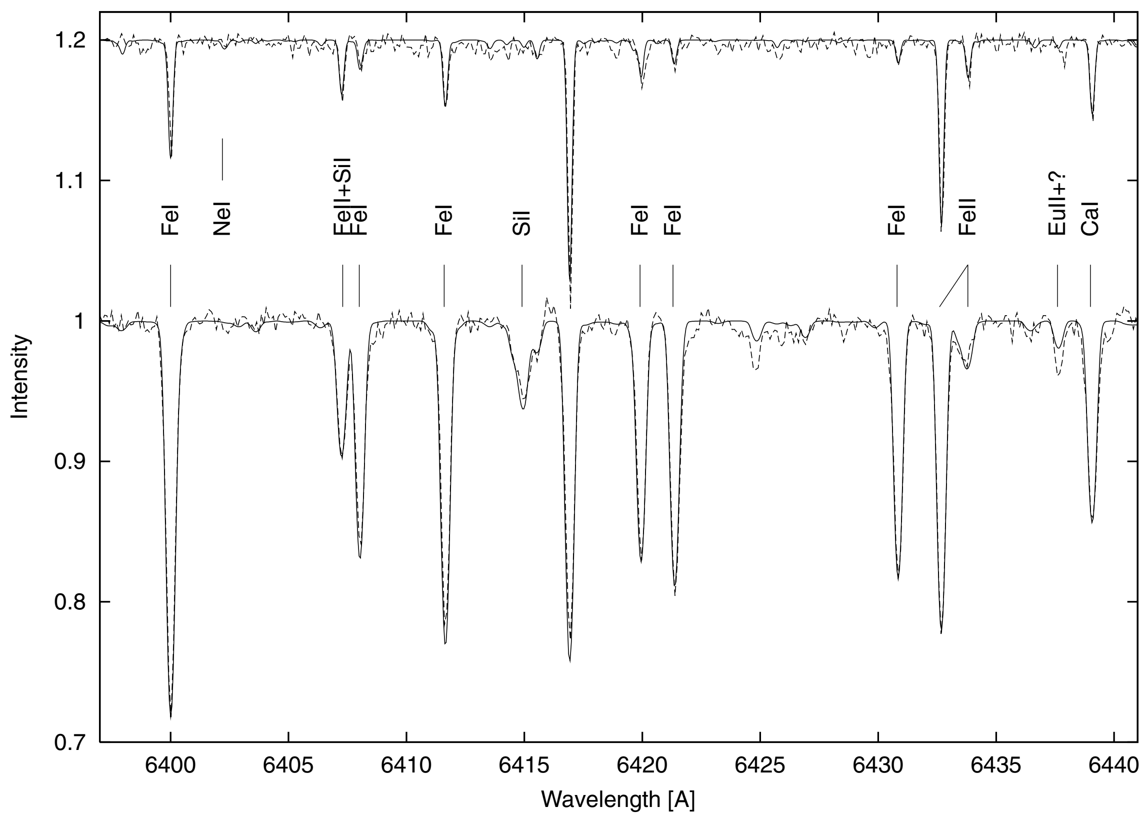

Figure 3. HD 33254 (bottom) and HD 198391 (top, shifted by +0.2 in intensity): dashes, observations; solid, synthetic spectrum.

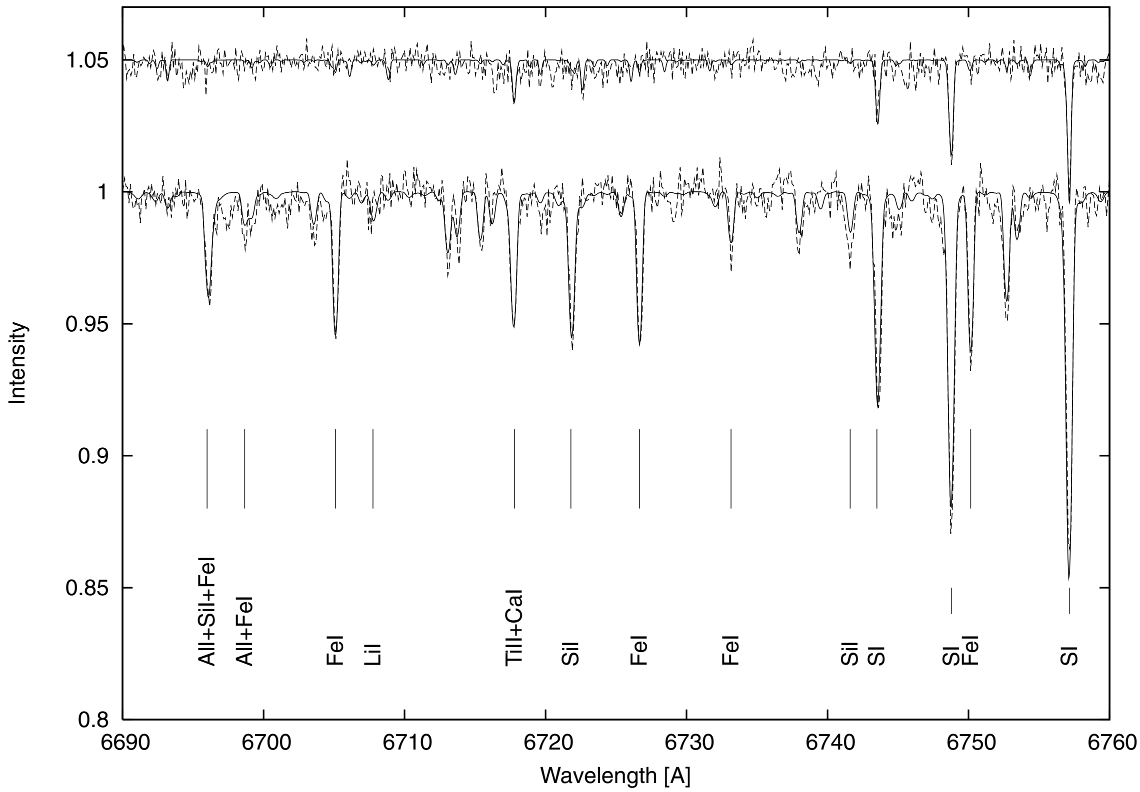

Figure 4. HD 33254 (bottom) and HD 198391 (top, shifted by +0.05 in intensity): dashes, observations; solid, synthetic spectrum.

is only approximate as such a value is almost comparable not only with the instrumental profile but also with microturbulence. Nevertheless, it is in very good agreement with Griffin et al. (2000), who from higher-resolution photographic spectra list a value of 6 km s^{-1} but do not include microturbulence. This gives us more confidence that our instrumental profile is well determined and that rotational velocities for even such sharp line stars are reasonable. It should make the star attractive for farther more detailed investigations with higher resolution, magnetic fields measurements. Microturbulence is lower than in HD 33254 which might reflect the gradual disappearance of the superficial convection zones at such temperatures due to the ionization of hydrogen. We were able to detect helium and it seems normal. Moreover, we can put an interesting constraint on neon abundance from the Ne I 6402 line. Neon seems deficient which looks like a prolongation of the neon deficit found in HgMn stars by Dworetsky & Budaj (2000) towards cooler regions. Including non-local thermodynamic equilibrium (NLTE) effects for this line should not affect the equivalent width by more than 15 per cent and can only make the deficit slightly more pronounced. This neon deficit is compatible with low radiative acceleration for neon and its gravitational settling in the atmospheres of cool HgMn stars (Budaj & Dworetsky 2002; Landstreet, Dolez & Vauclair 1998). In connection with this it is interesting to point out that in HRD the star is placed close to the region occupied by HgMn stars (see Fig. 2) and its stellar mass is within the region $2.5 < M < 2.9$ M$_\odot$ for which Adelman, Adelman & Pintado (2003) suggested that stars can evolve from HgMn towards an Am peculiarity in the course of their MS life. We can exclude any strong Li overabundance with respect to cosmic abundance. Carbon and oxygen are slightly deficient and nitrogen is probably normal but the listed C and N abundances are upper limits. S and Fe are slightly overabundant while calcium is essentially normal. This means that this is not a typical Am star and underlines the conclusions of Künzli & North (1998) that the Ca deficit ceases towards hotter stars. Thus, Ca is no longer a good measure of Am peculiarity and [Ca/Fe] is more appropriate. The abundance pattern is strikingly similar to Sirius and ranks this star with its temperature among hot Am stars. Ba has a serious enhancement. The synthetic Fe II 6480 line is too strong and its gf-value should be lower. Unfortunately, it is not observed on the Sun so we did not modify its gf-value.

5.3 HD 178449

The star HD 178449 (17 Lyr, HR 7261, BD+32 3326, HIP 93917, SAO 67835, ADS 12061A, WDS 19074+3230A, CCDM J19075+3231A, F0V) is known as an SB1 star. Its first orbit was published by Abt & Levy (1976). However, it turned out wrong and their data were reanalysed by Dworetsky (1983). Later, Abt & Morrell (1995) classified the star as Am but ascribed the same spectral types F1/F1/F1 from Ca II K, hydrogen and metal lines, respectively. They also derived the projected rotational velocity $v \sin i =$ 125 km s^{-1}. The star is the A component of ADS 12061. The B component is a 9.1-mag star and its separation (position angle) varied from 3.7 to 3.5 arcsec (from 331 to 301 deg) from 1830 to 1963 (Worley & Douglass 1997). Latest observations (Gili & Bonneau 2001) in 1997 resulted in the separation of 2.48 arcsec and position angle of 292.9 deg. We have included this star in the sample also for the purpose of testing the whole observational and analysis procedures at higher rotational velocities. It turns out that it is a very interesting object and requires special attention and a larger amount of observational data.

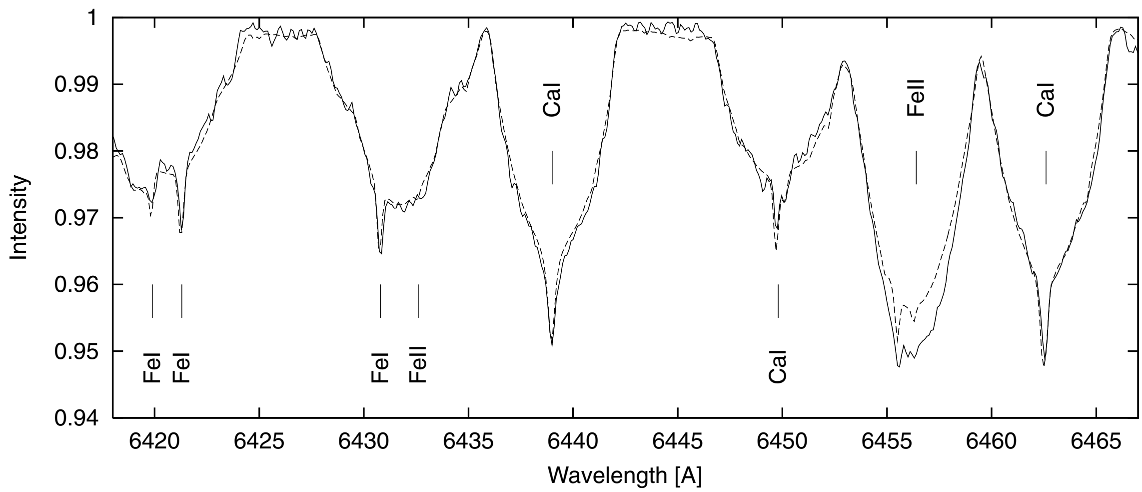

Figure 5. HD 178449: solid line, observed spectrum; dashes, computed spectrum of a binary (see the text).

We can confirm the high projected rotation velocity of this star and it seems even higher to us; we derived 139 km s^{-1}. Note that if the measurements of Abt & Morrell (1995) were scaled to the Royer et al. (2002) measurements the predicted velocity would be 138 km s^{-1}.[1] The major complication with this star is that at such a high velocity only strong lines can be seen. Broad lines are often blended which complicates radial velocity measurements, continuum rectification, microturbulence determinations and consequently all abundance analysis too.

A sharp-line secondary spectrum superposed on the broad primary spectrum was discovered in spectra 1–5. The broad and sharp sets of lines do not seem to have moved at all within the precision of our measurements ($\sigma = 1.5$ km s^{-1}) but there is an apparent shift of about 5 km s^{-1} between the broad and sharp spectrum with the sharp spectrum blue-ward. Consequently, spectra 1–5 were cross-correlated, sifted in radial velocity and co-added with the weights corresponding to their 1/(S/N)^2. The S/N ratio of the resulting spectrum is about 1700 and is shown in Fig. 5. The radial velocities were measured by the centre-of-mass method from the only line Ca I 6439 which is almost blend-free (Table 1). These, our radial velocities, are plotted together with the Abt & Levy (1976) data and the radial velocity curve determined from their measurements by Dworetsky (1983) in Fig. 6. It is apparent that our measurements are at least 20 km s^{-1} higher than the expected gamma velocity and that many measurements of Abt & Levy differ by more than 30 km s^{-1}! Something must be wrong with this star. Either the original measurements of Abt & Levy are not very precise or radial velocities change in a more complicated way than a simple orbital motion. The first version is quite possible if we take into account that from the photographic spectra they could have measured only strong and blended lines. This underlines the warning of Morbey & Griffin (1987) who argue that most orbits discovered by Abt & Levy should be reconsidered.

As to the origin of the secondary spectrum we can think about three alternatives: interstellar lines, shell lines or a second stellar spectrum. We exclude interstellar origin as many sharp lines originate from excited levels. There are several arguments supporting the idea that it could be a shell. Shell lines are mainly seen in highly rotating stars as well as in stars slightly above the MS which is the case with this star. A large difference in radial velocities between us and Abt & Levy could be naturally understood, as unexpected changes in shells are commonly observed. Arguments against the shell are that the star is rather cool and shells favour hotter stars. If it is a shell, it could also exhibit sharp lines at shorter wavelength such as Ti II 3913 or Ca II HK. We carried out special observations (Table 1, No 7) of this region but we could detect only an uncertain Ca II K blend but no convincing sharp-lined features within S/N = 150. Note that if it is a shell it would be expanding with a velocity of about 5 km s^{-1}.

There are several arguments favouring the stellar origin of the sharp spectrum. In this context we will refer to it as the Ab component and use Aa to denote the broad-lined primary. The sharp lines are mainly the Fe I and Ca I lines and the sharp component of Ca I 6439 is wider than those sharp Fe I lines. We do not see sharp Fe II lines. This indicates that sharp lines could originate in a dense and cooler atmosphere rather than in a low-density shell which would

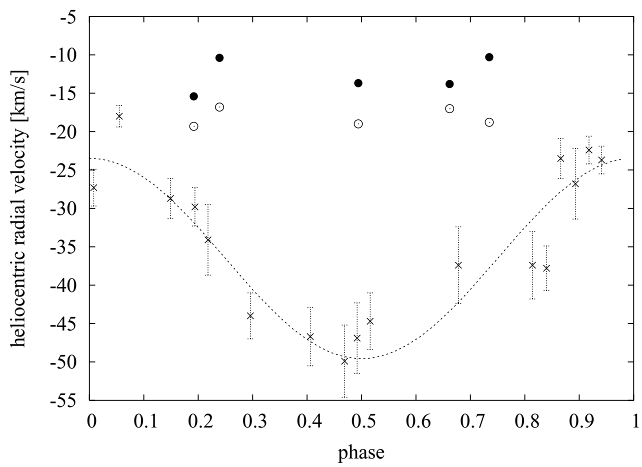

Figure 6. Radial velocities of HD 178449: full circles, our measurements of the primary spectrum; open circles, our measurements of the secondary spectrum; crosses, measurements of Abt & Levy (1976); line, radial velocity curve of Dworetsky (1983).

[1] This indicates that using the scaling of Royer et al. for the measurements of Abt & Morrell probably works fine for broad-line stars but may fail for sharp-line stars.

support higher ionization. We carried additional synthetic spectra calculations and realized that the sharp spectrum is well reproduced by these atmospheric parameters: $T_{\rm eff} = 5000$ K, $\log g = 4.5$ and light ratio $L_{\rm Aa}/L_{\rm Ab} = 47$ (we assumed solar chemical composition, $v \sin i = 2$ km s^{-1} and $\xi_{\rm turb} = 1$ km s^{-1}). This corresponds to a late G dwarf which is about 4.2 mag fainter at 6450 Å than the primary. Using the above stellar models we can predict the light ratio at 5500 Å (equivalent to V magnitude) to be $L_{\rm Aa}/L_{\rm Ab} = 55$ corresponding to $\Delta m = 4.4$. At 3920 Å, it would be $L_{\rm Aa}/L_{\rm Ab} = 78$, corresponding to $\Delta m = 4.7$. Thus, the sharp spectrum would be very difficult to see at a shorter wavelength and this could perhaps explain our negative result. An additional argument in favour of a stellar companion comes from HRD and Fig. 2 where the position of the Ab companion inferred from spectroscopy is in perfect agreement with the position of a 0.8 M$_\odot$ star and the positions of both Aa and Ab stars can be bridged by an isochron.

Consequently, we can speculate if our Ab component is not actually the visual B component which is about 3.9 mag fainter and so close that theoretically it could dilute the spectrum of the primary; but we think that this is not probable. Assuming circular orbit we can estimate from the known parallax and the angular separation that the minimum distance between the A and B companions would be about 150 au and, assuming $M_{\rm A}$, $M_{\rm B} = 1.67$, 0.8 M$_\odot$, respectively, the minimum orbital period of the B component would be about 1200 yr. Consequently, the maximum orbital velocity difference between the A and B components should not exceed 3.8 km s^{-1} while the minimum difference of about 5.5 km s^{-1} is observed between the Aa and Ab components. This is in perfect agreement with Tokovinin & Smekhov (2002) radial velocity measurements of the B component. The mean value of their six measurements obtained during 1995–1996 is -12.9 km s^{-1} while our mean radial velocity of the primary (Aa) spectrum is -12.7 km s^{-1}. Let us note at this point that Abt & Levy mentioned that B is the only member of this ADS system which has a common proper motion with A but their gamma velocity of the A component was -35 km s^{-1}. This might have misled Tokovinin & Smekhov and the B component was labelled as optical. A very different value of the radial velocity of HD 178449 is also listed in Wilson (1953): $+4$ km s^{-1}. Really, a lot of controversy about such a bright star.

Finally, considering all pros and cons, our conclusion, which should be checked by additional observations in the future, is that the sharp spectrum is most probably of stellar origin and that we have discovered a new Ab spectroscopic component of the system which has presently a constant shift of about 5 km s^{-1} in radial velocity.

A microturbulent velocity of about 2.5 km s^{-1} fits the available data best. Reliable abundances could be obtained only for three elements. Calcium is essentially normal while iron seems in deficit. In spite of high rotation we were able to detect lithium and its abundance is close to the cosmic one. Barium might be slightly overabundant. Thus, we do not see any Am characteristics mentioned by Abt & Morrell (1995) from our spectra in this star. On the contrary, the star, if analysed as a single star, seems deficient in iron – a feature already mentioned by Varenne & Monier (1999) in a few highly rotating stars. We would like to note that the possible secondary star is so faint that it should not affect $uvby\beta$ photometry of the star and the derived atmospheric parameters.

6 CONCLUDING REMARKS

Let us now return to the very beginning. Based on the short review in Section 1 it is apparent that Am peculiarity is embedded in a multidimensional space of 'parameters', with mass, age, rotation, orbital elements and mass ratio being probably the most primordial although not fully independent ones. As a rule it is difficult to distinguish the manifestation of one parameter from the other when working in only one dimension, as was done in most previous papers. We have to work in more dimensions which involves a more complex study of individual stars. In Section 2 we showed that we might expect the abundance anomalies in Am binaries to be modified by the already known tidal mechanism and we set up a program (described in Sections 3 and 4) to search for such effects. First, three stars were analysed in Section 5 of the paper. Any conclusions about the tidally driven abundance anomalies can, however, be drawn on the statistical grounds only and more Am binaries with $10 < P_{\rm orb} < 180$ d are under study. Nevertheless, we can speculate about the possible origin of the abundance anomalies found. Is it not the case that the pronounced Am anomalies of HD 33254 are due to its exceptional orbital elements? The star is not fully pseudo-synchronized as its pseudo-synchronization rotational velocity would be about 7 km s^{-1} (Budaj 1997) but it may have slow rotation, a sufficiently long orbital period to eliminate the tidal mixing but short enough ($<$180 d) to undergo the tidal interaction and hypothetical stabilization process. High eccentricity also seems to promote Am abundance anomalies. Thus, it does seem to be located in the region of very low intensity tidal currents in Fig. 1. On the other hand, Burkhart & Coupry (2000) argue that there are other similar binaries (HD 33204, 81 Tau, HD 73045) which do not exhibit such strong Li deficit. However, HD 33204 and HD 73045 have orbital periods too large to expect any significant tidal interaction and the orbit of 81 Tau is uncertain and not recognized by Pourbaix & Tokovinin (2001). We think the question is still open. On the contrary, HD 198391 might be pseudo-synchronized as its pseudo-synchronization rotational velocity would be about 35 km s^{-1}. It has moderate orbital period and even quite eccentric orbit so that more pronounced tidally driven abundance anomalies could be expected. However, it is a hot Am star and it might well be that the strong temperature effects took their chance and wiped the potential Ca deficiency. HD 178449 seems to have avoided these speculations as neither its Am character nor its original SB1 binary nature were confirmed and, although a new possible companion emerged, it would be on too remote an orbit to expect a tidal interaction. Note that the star is located within the hot edge of the Li gap and its high rotation, evolution status and Li content may put important constraints on the explanation of this feature.

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