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Abundance analysis of Am binaries and search for tidally driven abundance anomalies – III. HD 116657, HD 138213, HD 155375, HD 159560, HD 196544 and HD 204188

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ABSTRACT

We continue here the 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 of HD 116657, HD 138213, HD 155375, HD 159560, HD 196544 and HD 204188 were obtained in two spectral regions (6400–6500 and 6660–6760 Å). A synthetic spectrum analysis was carried out and the basic stellar properties, effective temperatures, gravities, projected rotational velocities, masses, ages and abundances of several elements were determined. We conclude that all six stars are Am stars.

These stars were put into the context of other Am binaries with $10 < P_{\rm orb} < 200$ d, and their abundance anomalies discussed in the context of possible tidal effects. There is a clear anticorrelation of the Am peculiarities with $v \sin i$. However, there seems also to be a correlation with the eccentricity and perhaps with the orbital period. The dependence on temperature, age, mass and microturbulence was studied as well. The projected rotational velocities obtained by us were compared with those of Royer et al. and Abt & Morrell.

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

1 INTRODUCTION

Am stars make up 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 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 and 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 step function of rotation (Iliev & Budaj 2008, and references herein; Abt 2000; Burkhart & Coupry 2000). 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 will not undergo considerable changes during the MS phase, or (2) 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 this, the Am phenomenon is apparently restricted to a well-defined region of the MS in the Hertzsprung–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), Budaj (1997) and Iliev et al. (1998) 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, δm_1 is a metallicity parameter that shows the difference in the dereddened m_1 index of $uvby\beta$ photometry between an Am star and a normal star of the same index, $f(m)$ is a mass function and P_p is the 'instantaneous' orbital period at periastron. The authors concluded that there are a number of subtle effects that are difficult to understand within the current framework of rotation and atmospheric parameters as the only agents determining Am star peculiarity.

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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.

This forced us to study the Am peculiarity and the orbital elements and $v \sin i$, mass, age as well. In order to explore the possible dependence of Am peculiarity on the orbital elements of the binary system, we started a systematic spectroscopic investigation of Am stars. A few tens of Am binaries from Budaj (1996) were chosen to be studied in detail. The following criteria were applied in order to compile the list of stars: targets with declination $\delta > -10^\circ$ and brighter than seventh magnitude in the V filter. In order to cover a full range of eccentricities and avoid strong synchronization effects, we have chosen only stars with orbital periods $10\,\mathrm{d} < P_{\mathrm{orb}} < 200\,\mathrm{d}$. No constraints were put on the rotational velocity.

In this connection, studies of individual Am binaries are very important (e.g. Fossati et al. 2007; Zverko et al. 2008; Zverko et al. 2009; Boffin 2010; Hubrig, González & Schöller 2010; Mikulashek et al. 2010; Quiroga, Torres & Cidale 2010). Obtaining new orbital elements of many Am binaries is also required to prove the dependence between orbital elements and Am peculiarity (Debernardi 2002; Carquillat & Prieur 2007; Zhao et al. 2007; Fekel & Williamson 2010).

This is the last in a series of papers (Budaj & Iliev 2003, hereafter Paper I, and Iliev et al. 2006, hereafter Paper II) aimed at comprehensive study of the Am peculiarity in multi-dimension parameter space involving the orbital elements, $v \sin i$, mass and age.

2 OBSERVATIONS AND SAMPLE STARS

Our spectroscopic observations were carried out with the 2-m Ritchie–Chretien–Coude telescope of the Bulgarian National Astronomical Observatory in the frame of our scientific project on Am stars in binary systems. As in the previous papers of the series, we observed each star in two spectral regions: 6400–6500 Å (Ca) and 6660–6760 Å (Li) (Table 1). For more details about the processing procedures, see these papers.

The focus of this paper is to continue the analysis of another six stars from the sample, namely HD 116657, HD 138213, HD 155375, HD 159560, HD 196544 and HD 204188.

3 ATMOSPHERIC PARAMETERS AND SPECTRUM SYNTHESIS

Relevant information about our program stars is summarized in Table 2. The $uvby\beta$ indices (dereddened using the UVBYBETA code of Moon & Dworetsky 1985) were taken from Renson (1991). Geneva and *UBV* photometry were from Mermilliod, Mermilliod & Hauck (1997). The improved *Hipparcos* parallaxes were taken from van Leeuwen (2007). 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. All these stars seem to be SB1 binaries or have only a very weak secondary spectrum, hence the possible influence of their companions on photometry was neglected.

A detailed spectrum synthesis of the spectral regions was accomplished following the same recipe as in the previous papers of the series.

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

N	Date	HJD	Exp.	Reg.	RV1	ΔRV1
		HD 116657				
1	04.01.2001	1913.554	40	Ca	−11.1	2.6
2	04.01.2001	1913.594	40	Li	−11.1	2.8
		HD 138213				
1	10.06.2001	2071.325	45	Ca	−12.4	1.7
2	09.06.2001	2070.357	45	Li	−11.2	3.1
		HD 155375				
1	10.06.2001	2071.392	90	Ca	24.7	2.8
2	21.08.2001	2508.300	115	Ca	19.1	1.9
3	26.08.2002	2513.251	90	Ca	25.6	1.8
4	28.08.2002	2515.292	40	Ca	24.7	1.5
5	22.09.2007	4366.270	60	Ca	8.4	2.8
6	23.09.2007	4367.245	90	Ca	10.7	1.9
7	24.09.2007	4368.229	60	Ca	14.9	2.0
8	09.06.2001	2070.430	75	Li	24.6	5.3
		HD 159560				
1	10.06.2001	2071.453	40	Ca	−23.7	2.5
2	23.08.2007	4336.395	25	Ca	−13.8	2.2
3	25.08.2007	4338.442	20	Ca	−12.7	2.9
4	11.06.2001	2072.384	45	Li	−24.6	2.7
		HD 196544				
1	10.06.2001	2069.546	60	Ca	−29.9	2.5
2	28.08.2001	2150.278	100	Ca	−7.2	3.0
3	02.09.2001	2155.332	30	Ca	12.6	4.7
4	18.05.2002	2412.560	40	Ca	−19.9	2.4
5	10.08.2000	1767.324	115	Li	21.1	4.1
		HD 204188				
1	23.07.2000	1749.437	180	Ca	−18.5	2.5
2	22.07.2000	1748.454	260	Li	−8.0	2.9

4 RESULTS FOR INDIVIDUAL STARS

The abundances obtained by synthetic spectrum-fitting analysis are expressed relative to the Sun in terms of $[\mathrm{N/H}] = \log(\mathrm{N/H})_\star - \log(\mathrm{N/H})_\odot$ 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 used the determined absolute magnitudes, 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 Fig. 2.

Radial velocities, projected rotational velocities and microturbulent velocities determined as by-products are also listed in Tables 1 and 3. A comparison between measured radial velocities of the six stars and predicted radial velocity curves is shown in Fig. 3. For the Am stars with $v \sin i < 50\ \mathrm{km\,s^{-1}}$, the radial velocities of the primary stars were measured using the cross-correlation of the whole

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

Star	HD 116657	HD 138213	HD 155375	HD 159560	HD 196544	HD 204188
			UBV photometry			
V	2.227^{T}	6.146	6.586	4.865	5.433	6.078
$B-V$	0.057^{T}	0.10	0.085	0.279	0.052	0.22
$U-B$	–	0.12	0.086	0.068	0.039	0.06
			$uvby\beta$ photometry			
$E(b-y)$	−0.010	−0.014	−0.005	0.001	−0.010	0.000
$(b-y)_0$	0.063	0.046	0.047	0.175	0.022	0.142
m_0	0.239	0.191	0.197	0.208	0.186	0.199
c_0	0.911	1.141	1.025	0.747	1.014	0.777
β	2.886	2.860	2.885	2.772	2.911	2.806
T_{eff}	8470	8430	8560	7460	9090	7780
$\log g$	4.32	3.61	4.09	4.14	4.33	4.30
			Geneva photometry			
U	–	1.648	1.561	1.478	1.501	1.434
V	–	0.825	0.842	0.609	0.905	0.677
$B1$	–	0.909	0.910	0.971	0.902	0.953
$B2$	–	1.445	1.449	1.404	1.469	1.422
$V1$	–	1.524	1.539	1.334	1.601	1.390
G	–	1.989	2.000	1.732	2.084	1.807
T_{eff}	–	8403	8657	7321	9301	–
$\log g$	–	3.65	4.02	4.26	4.29	–
P_{orb}	175.6[1]	105.95[2]	23.2[3]	38.0[4]	11.0[5]	21.72[5]
e	0.46[1]	0.0[2]	0.42[3]	0.03[4]	0.23[5]	0.0[6]
π	41.73 ± 0.61	6.37 ± 0.29	10.13 ± 0.45	32.80 ± 0.18	17.26 ± 0.33	21.57 ± 0.56
M_V	0.33	0.17	1.61	2.44	1.62	2.75
			Adopted atmospheric parameters			
T_{eff}	8470	8500	8610	7390	9200	7780
$\log g$	4.32	3.50	4.06	4.20	4.31	4.30

Notes:
[1] Gutmann (1965); [2]Lucy & Sweeney (1971); [3]Debernardi (2002); [4]Margoni, Munari & Stagni (1992); [5]Harper (1935); [6]Batten, Fletcher & Mann (1978); [T]*Hipparcos* and Tycho catalogue (ESA 1997); T_{eff} is in K, $\log g$ in CGS units, P_{orb} in d 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 $\log(N_{\mathrm{el}}/N_{\mathrm{H}}) + 12.00$.

	Sun	HD 116657	HD 138213	HD 155375	HD 159560	HD 196544	HD 204188
Li	1.10	≤+2.08	≤+2.2	≤+1.88	+1.68	≤+2.4	≤+0.6
C	8.52	≤−0.62	≤−0.18	≤−0.11	−0.57	≤−0.34	−0.82
O	8.83	≤−0.38	−0.13	≤−0.22	≤−0.16	≤−0.29	−0.13
Al	6.47	+0.30	–	–	–	–	–
Si	7.55	+0.00	+0.34	+0.05	+0.01	+0.10	+0.04
S	7.33	+0.10	+0.19	+0.0	+0.03	+0.15	−0.31
Ca	6.36	−0.42	+0.11	−0.64	−0.76	−0.50	−0.18
Ti	5.02	+0.00	+0.28	+0.14	−0.04	+0.24	+0.21
Fe	7.50	+0.34	+0.29	+0.22	+0.29	+0.27	+0.07
Ni	6.25	+0.67	+0.40	+0.65	+0.51	–	+0.23
Ba	2.21	–	+2.15	+1.85	+1.64	+1.19	+1.41
ξ_{turb}	–	2.0	2.0	2.1	2.7	2.4	2.0
$v \sin i$	–	51	32	31	42	43	36
M	–	2.10	2.49	2.26	1.62	2.20	1.67
$\log T$	–	8.72	8.43	8.05	8.96	7.43	6.5*
$\log$ *TAMS*	–	8.77	8.8	8.99	9.32	9.02	9.28

Notes:
Sun: abundances are taken from Grevesse & Sauval (1998) (recall that the normal lithium abundance in hot stars or meteorites is [Li/H] = 2.00); microturbulence: ξ_{turb} and $v \sin i$ are in km s^{-1}, M is mass in M$_{\odot}$, age T and the terminal-age main sequence *TAMS* are given in yr; *: the age is only an upper limit (see details in the text).

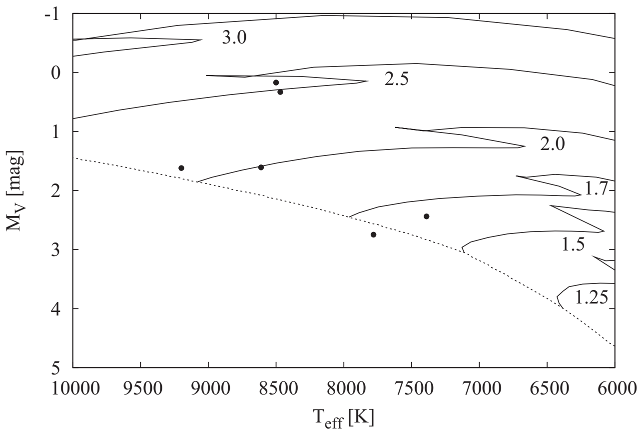

Figure 1. The location of our six stars in the HR diagram. Evolutionary tracks for $M = 3.0, 2.5, 2.0, 1.7, 1.5$, and $1.25\,\mathrm{M}_{\odot}$ are shown by solid lines, while an isochrone for $\log T = 3.0$ in yr (ZAMS) is shown by the dotted line (Lejeune & Schaerer 2001).

spectral region of the observed spectrum with the synthetic spectra. For the fast-rotating star (HD 116657) with $v \sin i > 50\,\mathrm{km\,s^{-1}}$, 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 Budaj & Iliev (2003) with the same telescope configuration and centre-of-mass method demonstrated, using the example of the fast-rotating star (HD 178449, $v \sin i = 139\,\mathrm{km\,s^{-1}}$), that the standard deviation of such radial velocity measurements was smaller than $2\,\mathrm{km\,s^{-1}}$. A discussion of the individual stars follows.

4.1 HD 116657

HD 116657 (ζ UMa B, HR 5055, ADS 8891 B, BD +55 1598B, SAO 28738, CSV 101382, A1m) is a part of the Mizar system. This system was the first double star observed photographically. HD 116657 is the fainter star of the system, where both stars are spectroscopic binaries.

The first spectral classification was given by Roman (1949): A2/A8/A7 (Ca II/H/metal lines). Later, Cowley et al. (1969) determined the spectral class as A1 from *K* lines and Levato & Abt (1978) as A2/A7/A9 from K/H/metallic lines. Finally, Abt & Levy (1985) determined the spectral class of HD 116657 as A1/A4/A3 according to K/H/metallic lines. The orbital elements of the binary system were obtained by Gutmann (1965): $P_{\mathrm{orb}} = 175.6$ d, $K = 6.4\,\mathrm{km\,s^{-1}}$, $e = 0.463$, $V_0 = -9.3\,\mathrm{km\,s^{-1}}$, $\omega = 6\overset{\circ}{.}9$. There have been numerous evaluations of the projected rotational velocity given by different authors. Meadows (1961) and Abt & Moyd (1973) measured $v \sin i = 50\,\mathrm{km\,s^{-1}}$. Dobrichev (1985) gave a close value ($v \sin i = 52\,\mathrm{km\,s^{-1}}$) while Slettebak (1954) obtained a higher velocity ($v \sin i = 75\,\mathrm{km\,s^{-1}}$). Abt & Morrell (1995) measured the projected rotational velocity as $v \sin i = 51\,\mathrm{km\,s^{-1}}$, but scaling this value to the results of Royer et al. (2002) changed the velocity to $v \sin i = 61\,\mathrm{km\,s^{-1}}$. Monier (2005) also obtained $v \sin i = 61\,\mathrm{km\,s^{-1}}$. Our value of $v \sin i = 51\,\mathrm{km\,s^{-1}}$ is very close to the values given by the majority of authors.

A few evaluations of effective temperature have been noted in the literature. The first value, given by Cayrel de Strobel (1960), determined HD 116657 as a very cool star: $T_{\mathrm{eff}} = 5130$ K. Later values have given higher temperatures for the star. According to Smith (1971) the effective temperature was $T_{\mathrm{eff}} = 8800$ K, and according to King et al. (2003) and Monier (2005) it was $T_{\mathrm{eff}} = 8425$ K. Our value of $T_{\mathrm{eff}} = 8470$ K is very close to the value of these authors.

The abundances of Ca, Fe, S are determined with good precision. For lithium we can only set an upper limit and claim that Li is not overabundant relative to the cosmic Li abundance. However, there is an indication of an Li line. If this is confirmed then Iliev et al. (1998)'s Li abundance would be underestimated. Also, the values listed for C and O are only upper limits. According to our analysis, Al is overabundant and Si seems normal from only one line, Si I λ6721 Å. Ti could be evaluated only approximately to be normal

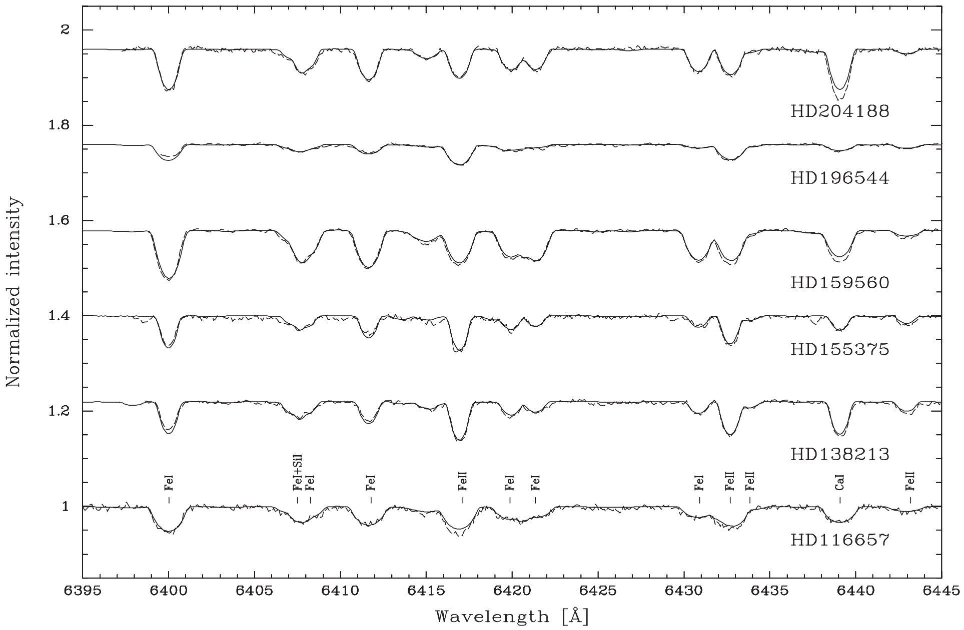

Figure 2. Measured radial velocities as listed in Table 1 (dots) in comparison with the predicted radial velocity curves (solid lines) versus phase. Orbital elements are taken from the appropriate references shown in Table 2.

from two blends of Ca I λ6717 Å and Fe I λ6678 Å. Ni is found to be overabundant. Some Fe II lines are stronger than expected and this might indicate not only higher microturbulence or effective temperature but also lower gravity.

4.2 HD 138213

HD 138213 (HR 5752, HIP 75770, BD + 47 2227) is a spectroscopic binary star. It was classified for the first time as a marginal metallic-line star A5m: by Cowley et al. (1969). Later, Eggen (1976) determined HD 138213 as a possible Am star based on photometry and Floquet (1975) suggested that the star was spectroscopically variable. According to Abt & Morrell (1995), the star was A2 IV. The orbital elements were taken by Lucy & Sweeney (1971): $P_{\rm orb} = 105.95$ d, $K = 10.8$ km s^{-1}, $e = 0$, $V_0 = -17.10$ km s^{-1}, $\omega = 0^{\circ}$. Our radial velocities do not agree very well with the predicted velocity curve. This might be due to a small phase shift that accumulated over the years. There have been a few evaluations of the projected rotational velocity. Abt (1975) gave $v \sin i = 30$ km s^{-1} but later corrected it to $v \sin i = 45$ km s^{-1} (Abt & Morrell 1995). Royer et al. (2002) scaled this value to their system and determined the velocity as $v \sin i = 54$ km s^{-1}. Our value is closer to the result given by Abt (1975): $v \sin i = 32$ km s^{-1}.

Our analysis confirms that HD 138213 is a marginal Am star: Fe is overabundant and O is underabundant. Ca has almost solar abundance. For C and Li we give only the upper limits.

4.3 HD 155375

HD 155375 (HR 6385, BD +12 3161, HIP 84036, SAO 102632, A1m) is a spectroscopic binary star. Osawa (1958) determined the spectral class of the star as A1/A3/A5 from K/H/metallic lines and Cowley et al. (1969) as A1. Later Abt & Morrell (1995) specified it as A2 III class and Paunzen et al. (2001) as A3 V class. Abt & Morrell (1995) also determined the projected rotational velocity as $v \sin i = 25$ km s^{-1}, but scaling this value to the system of Royer et al. (2002) the latter changed the velocity to $v \sin i = 33$ km s^{-1}. Our value of $v \sin i = 31$ km s^{-1} is in good agreement with the Royer et al. (2002) result. We used the orbital elements given by Debernardi (2002): $P_{\rm orb} = 23.25$ d, $K = 31.42$ km s^{-1}, $e = 0.422$, $V_0 = 1.03$ km s^{-1}, $\omega = 114^{\circ}.86$. The radial velocities measured from our spectra are in excellent agreement with the radial velocities calculated using these elements (see Fig. 3).

There are many Fe lines in the spectral region of 6400–6500 Å, so the abundance of Fe is very well determined. Ca is underabundant. The abundances given in Table 3 for C and O are upper limits. The situation with Li is the same as in the case of HD 116657: the Li line is very weak and the obtained Li abundance is only an upper limit.

More than one spectrum has been obtained in order to check the possible variability of some lines in the spectrum of HD 155375. As is seen, a few lines have changed their profiles (see Fig. 4). The relative changes of two lines, Fe I λ6419.95 Å and Fe I λ6421.35 Å, are the most obvious. Two calcium lines, Ca I λ6439.08 Å and Ca I λ6462.57 Å, have also shown changes. The centre of the lines has changed and also some features can be seen emerging from the blue side of the lines. All these observable clues force us to suspect HD 155375 as a new SB2 star.

4.4 HD 159560

HD 159560 (ν^2 Dra, HR 6555, BD +55 1945, HIP 85829, SAO 30450, ADS 10628 A, A4m) is a member of a visual binary system. The angular separation between the components is 61.9 arcsec. Both components of the binary system are Am stars. There have been many determinations of the stellar spectral class in the literature. The first evaluation was given by Slettebak (1949): A2/F0/F5 IV from K/H/metallic lines. Later, the author specified the spectral class from H lines as A7 (Slettebak 1963). According to Abt & Cardona (1984), the star was A4/F2V/F3. Cowley et al. (1969) also determined the spectral class of HD 159560 as A4 from H lines. The evaluations of the projected rotational velocity of the star have

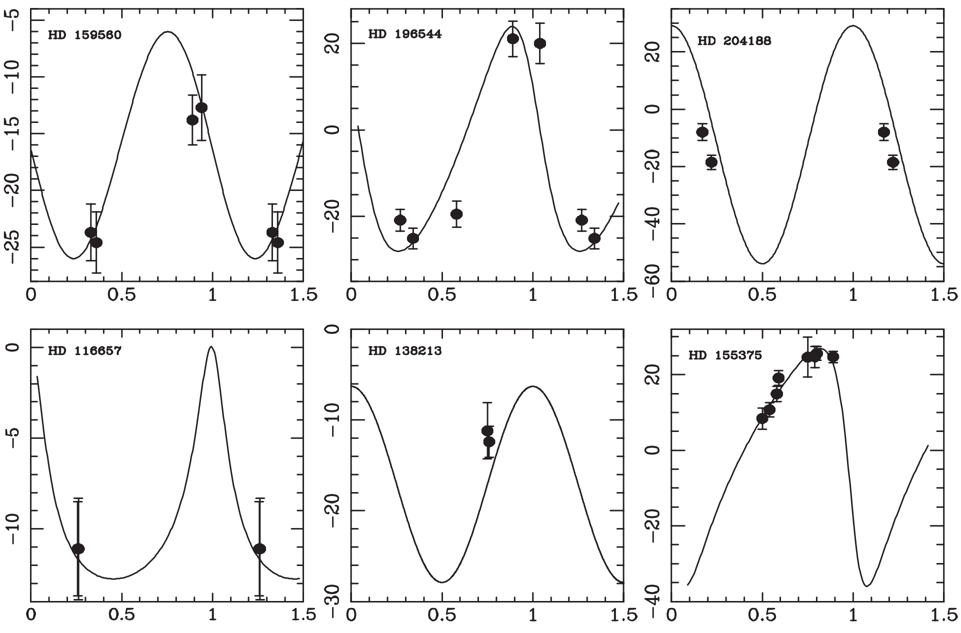

Figure 3. Synthetic (solid) and observed (dashed) spectra of all of our programme stars. The observed spectra were shifted to the laboratory frame of synthetic spectra. A proper shift to the vertical coordinate was applied to all but the lowest spectrum.

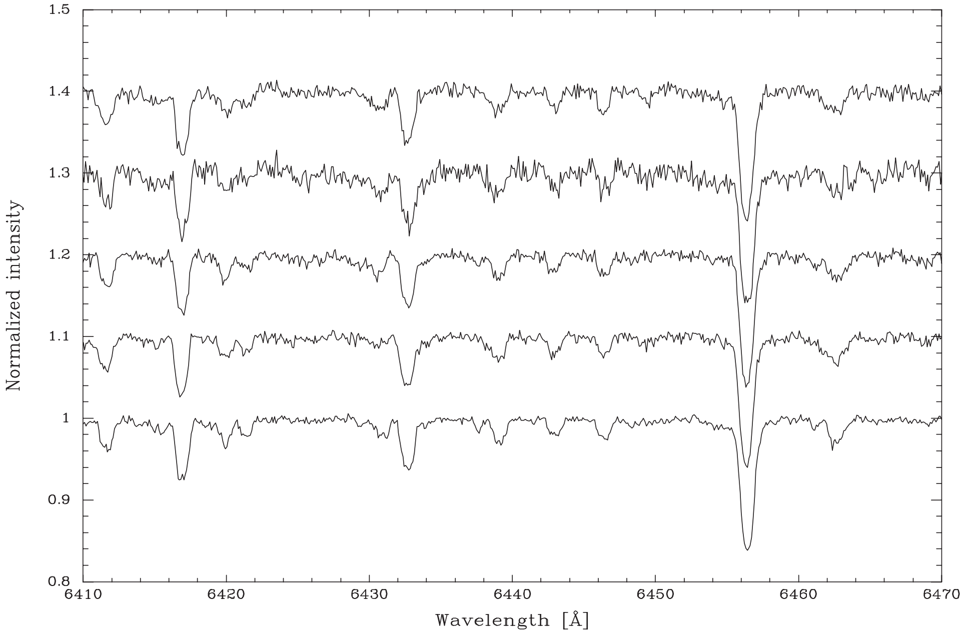

Figure 4. Observed spectra of HD 155375. A proper shift to the vertical coordinate was applied to all but the lowest spectrum. Spectra with low signal-to-noise ratio are not shown in the figure.

been very different. Abt & Moyd (1973) gave $v \sin i = 35\,\mathrm{km\,s^{-1}}$, Böhm-Vitense & Dettmann (1980) $v \sin i = 47\,\mathrm{km\,s^{-1}}$, Abt & Levy (1985) $v \sin i = 50\,\mathrm{km\,s^{-1}}$ and Abt & Morrell (1995) $v \sin i = 58\,\mathrm{km\,s^{-1}}$. Finally, Royer et al. (2002) determined the rotational velocity of the star as $v \sin i = 68\,\mathrm{km\,s^{-1}}$ scaled from the result of Abt & Morrell (1995). We obtained $v \sin i = 42\,\mathrm{km\,s^{-1}}$ and this is the value of the rotational velocity we used for spectrum synthesis. We used the two different set of orbital elements given by Abt & Levy (1985) and Margoni et al. (1992) in order to check our radial velocities. Our results are in good agreement with the radial velocity curve obtained by using the orbital elements of the latter authors (see Fig. 3). They gave the following orbital elements: $P_{\mathrm{orb}} = 38.034$ d, $K = 10.0\,\mathrm{km\,s^{-1}}$, $e = 0.03$, $V_0 = -16.0\,\mathrm{km\,s^{-1}}$, $\omega = 92^{\circ}$.

Our abundance results define the star as an Am star. The line of Li I λ 6707 Å is well identified and is relatively stronger compared with the other stars in this investigation. That is why the obtained abundance of Li is well-determined.

4.5 HD 196544

HD 196544 (ι Del, HR 7883, BD +10 4339, HIP 101800, SAO 106322) is an A2V spectroscopic binary star. Adams (1912) determined the stellar radial velocity for the first time and discovered that it was variable. He classified the star as an A2 spectral type star. Later Osawa (1959) determined the spectral class as A2 V according to the MK system: the Yerkes Spectral Atlas and as A4 from metallic lines. Levato (1975) confirmed the spectral class as A2 V and obtained a projected rotational velocity of $v \sin i = 55\,\mathrm{km\,s^{-1}}$ but later revised the velocity to $v \sin i = 60\,\mathrm{km\,s^{-1}}$ (Garcia & Levato 1984). On the other hand, Abt & Morrell (1995) classified the star as A1 IV and gave a smaller value of the rotational velocity: $v \sin i = 30\,\mathrm{km\,s^{-1}}$. Royer et al. (2002) derived the projected rotational velocity and after merging it with the data available obtained $v \sin i = 41\,\mathrm{km\,s^{-1}}$. The orbital elements were derived by Harper (1935): $P_{\mathrm{orb}} = 11.039$ d, $K = 26.0\,\mathrm{km\,s^{-1}}$, $e = 0.23$, $V_0 = -4.9\,\mathrm{km\,s^{-1}}$, $\omega = 61\overset{\circ}{.}8$. Again, as in the case of HD 138213, the differences between our radial velocity measurements and the predicted velocity curve are due to a small phase shift accumulated over the years.

There have been a few element abundances published in the literature. Lemke (1989), Lemke (1990) and Rentzsch-Holm (1997) gave the abundances of Fe, Ti, C, Ba, N and S using the atmospheric parameters $T_{\mathrm{eff}} = 9100$ K and $\log g = 4.3$, which were very close to our values (see Table 2).

According to the abundances obtained by us, HD 196544 seems to be an Am star. The abundances of Fe and Ca are very well determined as Ca is underabundant and Fe is overabundant. The Li line of 6707 Å is very weak and the abundance of Li is determined as only an upper limit. Other elements like C, O and Ti have weak lines in this spectral region, so their abundances should be scrutinized as upper limits. The differences between the abundances of Fe, Ti and C obtained by us and published by Lemke (1989) are within the errors.

4.6 HD 204188

HD 204188 (IK Peg, HR 8210, HIP 105860, BD +18 4794, WD 2124+191, A8m) is an interesting single-lined spectroscopic binary with a companion star that is a massive white dwarf. Cowley et al. (1969) identified HR 8210 as a marginal Am star and determined the spectral class as A8m: but Abt & Bidelman (1969) identified it as a definite Am star. According to Bertaud (1970), the spectral class of HR 8210 was between A5 and F0. Later Guthrie (1987) in his study of the calcium abundances in metallic-line stars found that Ca was of almost solar abundance. The most completed spectral identification was made by Abt & Morrell (1995): A6/A9/F0 from K/H/metallic lines. Kurtz (1978) obtained that the primary Am star was also a δ Sct star. Until now there have been only a few stars that combine in one and the same object such contradictory characteristics. The first orbit determination was made by Harper (1927), who found a period of about 27 days and an almost circular orbit. Later he clarified the period (Harper 1935) and Batten et al. (1978) assumed the eccentricity to be $e = 0$. We used the orbital parameters from the Ninth Catalogue of Spectroscopic Binary Orbits (SB9: Pourbaix et al. 2004): $P_{\mathrm{orb}} = 21.724$ d, $K = 41.5\,\mathrm{km\,s^{-1}}$, $e = 0$, $V_0 = -12.4\,\mathrm{km\,s^{-1}}$, $\omega = 0°$. There have been many evaluations of the projected rotational velocity of IK Peg in the literature, from $v \sin i = 80\,\mathrm{km\,s^{-1}}$ (Levato 1975) to $v \sin i = 31\,\mathrm{km\,s^{-1}}$ (Abt & Morrell 1995). Royer et al. (2002) determined the projected rotational velocity as $v \sin i = 40\,\mathrm{km\,s^{-1}}$, scaling the results of Abt & Morrell (1995). The projected rotational velocity obtained by us, $v \sin i = 36\,\mathrm{km\,s^{-1}}$, is in the range of Abt & Morrell (1995) and Royer et al. (2002) and very close to the values given by Rodriguez, Lopez-Gonzalez & Lopez de Coca (2000).

The iron-peak elements like Fe, Ti and Ni are slightly overabundant and those of Ca and O underabundant. For Li, we present only an upper limit. As for the other stars of this study, Ba is overabundant. These results, as well as the atmospheric parameters, are in good agreement with the results of Smalley et al. (1996). Our abundance analysis confirms that HD 204188 is a mild metallic-line star.

The age obtained for this star is determined with poor accuracy. We agree with Künzli & North (1998), who noticed the difficulty of determining stellar age properly when a star is near the zero-age main sequence (ZAMS).

5 TIDAL, ROTATION AND EVOLUTION EFFECTS IN AM PHENOMENA

Following the systematic search for abundance anomalies of Am stars driven by tidal effects, we continued by studying the dependences of the chemical abundances on the orbital elements of the binary systems, the projected rotational velocity and the physical parameters of Am stars like mass, age and temperature. The main advantage of our analysis is the homogeneity of the observational material we used: all data were obtained at one telescope with the same spectrograph and detector as well as processed with the same data reduction package and analysed with the same code SYNSPEC.

As is well known, Am peculiarities are mainly manifested through Ca deficit and Fe overabundances and they can be represented in a reliable way through the values of [Ca/Fe], where [Ca/Fe] = [Ca/H]−[Fe/H]. This ratio would multiply the effect of Am peculiarities, because these two elements have shown opposite behaviour. Also, the lines of both elements get weaker with increasing temperature and consequently the [Ca/Fe] ratio is not very sensitive to uncertainties in the effective temperature.

Up to now, 15 stars from our sample have been fully processed. The results are taken from this work and also from Papers I and II. Two of the stars in this sample, HD 178449 and HD 18778, were found not to be Am stars. They are shown in the figures but not included in the analysis.

First we investigate the dependences of [Ca/Fe] on the eccentricity (see Fig. 5). Despite some scatter in the data, there seems to be a trend like that mentioned earlier by Budaj (1997) and Iliev et al. (1998). The correlation coefficient is -0.55 ± 0.05. One star, HD 198391, which is denoted by an asterisk in the figures, is distinguished from the common trend. This star is the hottest star in the sample and it is not a typical Am star (Paper I). The star could be a transitional object between Am and the hotter HgMn stars because of its position in the HR diagram close to the region occupied by HgMn stars and also its abundances (for more details see Paper I). Namely, Am peculiarities increase ([Ca/Fe] decreases) with increasing eccentricity of the binary system. The dependence of [Ca/Fe] on the orbital period shown in Fig. 6 is not so clear, but still there is a tendency for the metallicity to increase towards longer periods. Of course, these two parameters characterizing the binary system, eccentricity and period are not fully independent because of the synchronization and circularization of the orbits. This was the main reason to analyse only stars with periods between 10 and 200 d. The comparison of the three parameters metalicity, eccentricity and period simultaneously in a 3D graph (see Fig. 7) showed us that there was not any correlation between period and eccentricity over the whole range of periods, which extends even beyond 150 d.

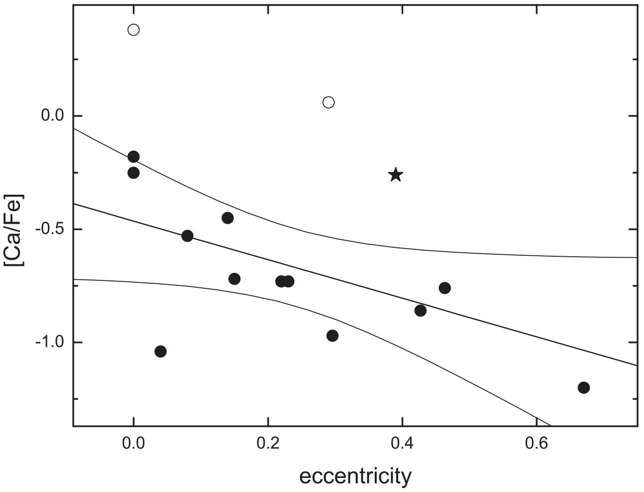

Figure 5. [Ca/Fe] versus the eccentricity of the orbit. A least-squares regression line and the 95 per cent confidence limits are drawn. The correlation coefficient is -0.55 ± 0.05. HD 198391 is denoted by an asterisk. Two non-Am stars, HD 178449 and HD 18778, denoted by open circles are given only for completeness and are not included in the analysis.

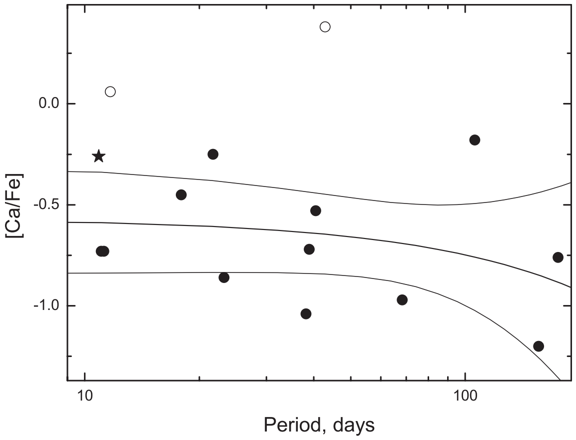

Figure 6. [Ca/Fe] versus the orbital period. The periods are presented on a logarithmic scale for more clarity. The correlation coefficient is -0.33 ± 0.06. The symbols are the same as in the previous figure.

We also study the dependence of the Am peculiarities on the projected rotational velocity of the Am stars (see Fig. 8). In general, there is a clear trend of increase in peculiarity (decrease of [Ca/Fe]) towards small values of $v \sin i$: the correlation coefficient is $+0.85 \pm 0.04$. Besides the hottest star already mentioned, HD 198391, two other stars, HD 138213 and HD 204188 which are both marginal Am stars, do not follow the common trend. The fact that these two stars depart from the clear smooth correlation of metallicity and $v \sin i$ indicates that rotation is not the only agent responsible for

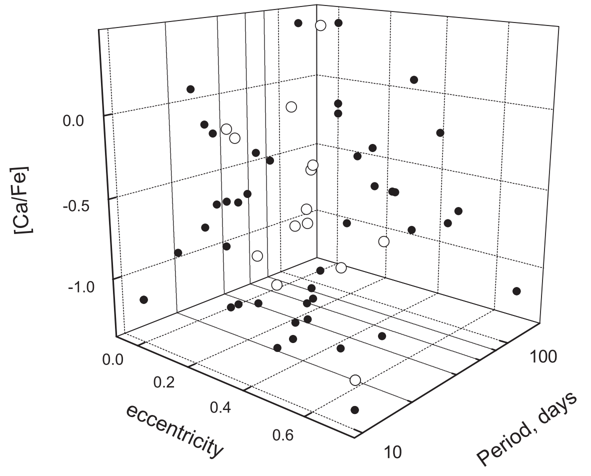

Figure 7. The dependence between [Ca/Fe], the eccentricity and the orbital period. Open circles stand for plane projections.

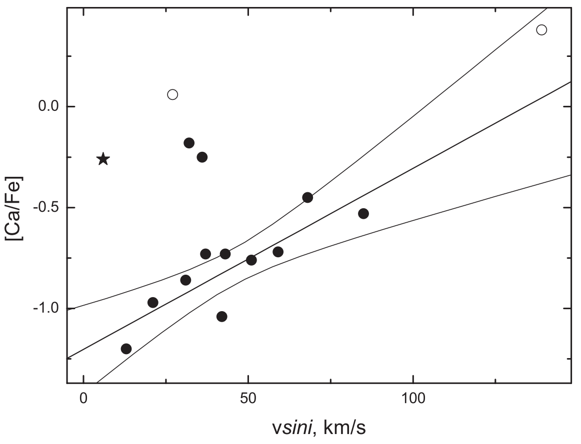

Figure 8. The dependence between [Ca/Fe], the eccentricity and the projected rotational velocity. Again, open circles stand for plane projections.

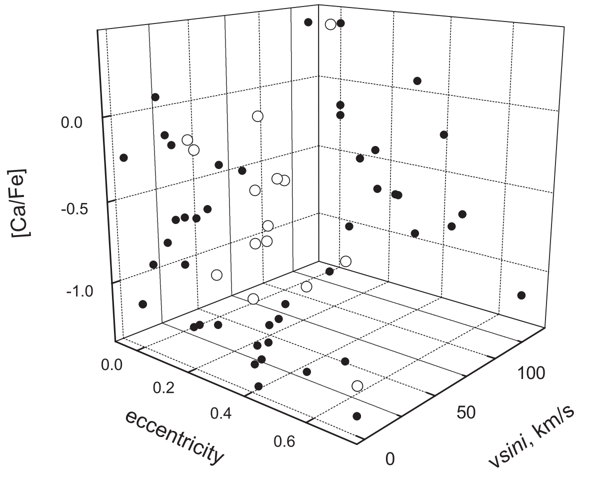

Figure 9. [Ca/Fe] versus the projected rotational velocity. The correlation coefficient is +0.85±0.04. The symbols are the same as in Fig. 5.

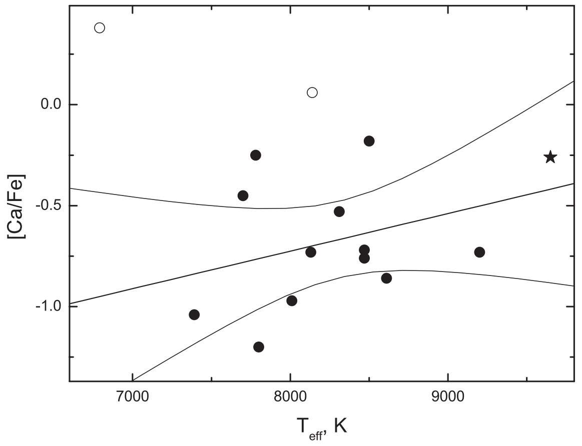

Figure 10. [Ca/Fe] versus the effective temperature. The correlation coefficient is +0.36 ± 0.06. The symbols are the same as in Fig. 5.

this peculiarity. It confirms our claims from Iliev et al. (1998) that the low Am peculiarity in these two systems is due to their small eccentricity. Again, in order to check the possible correlation between the parameters studied we tried to combine [Ca/Fe], the eccentricity and $v \sin i$ in a 3D graph (see Fig. 9). We obtained a weak negative correlation between the eccentricity and the projected rotational velocity: faster rotating stars tended to have smaller eccentricities.

The dependence of the Am peculiarity on the effective temperature is plotted in Fig. 10. There might be a trend of decrease in peculiarity with temperature: the correlation coefficient is +0.36 ± 0.06.

We sought a possible dependence of the Am peculiarity on the age and the mass of the stars. With the exception of one star, HD 196544, the other stars studied have very close ages: the difference between the youngest and the oldest star is 0.51 in $\log T$ (where T is the age in years). The majority of the masses of the stars also lie in a very short interval, 0.5 in solar masses. As a result, from all our data we cannot see any signs of dependence between these parameters (mass and age) and the Am peculiarity.

We also studied the connection between the microturbulence and the effective temperature (see Fig. 11). There seems not to be any dependence between these parameters for the temperature region 7000–9000 K. At higher temperatures, however, it is possible to claim that the microturbulence decreases with increasing temperature. These results fit relatively well with the conclusion given by Burkhart & Coupry (1992). The microturbulence is a pure fitting parameter, which brings into agreement the abundances from weak and strong lines. It does not necessarily have the meaning of existing turbulent motion. Nevertheless, this behaviour is in agreement with expectations and with the fact that superficial convective zones become thinner at higher temperatures and cease at about 10 000 K. We also studied a possible dependence of the Am peculiarities on the microturbulence, but there is no clear correlation. Apparently, the microturbulence does not seem to destroy the Am peculiarity.

We compared our measurements of the projected rotational velocities of the programme stars with those obtained by Abt & Morrell (1995) and Royer et al. (2002). As is seen from Fig. 12, our measurements are in good agreement with the results of these authors. The velocities of Abt & Morrell (1995) seem to be closer to our values while those of Royer et al. (2002) are often slightly higher.

6 CONCLUSIONS

In this third and final paper in the series, we have analysed another six binaries from our sample and derived their chemical composition, temperatures, gravities, projected rotational velocities, masses and ages. The obtained abundances of certain elements allowed us to conclude that these stars are Am stars. We suggested that one

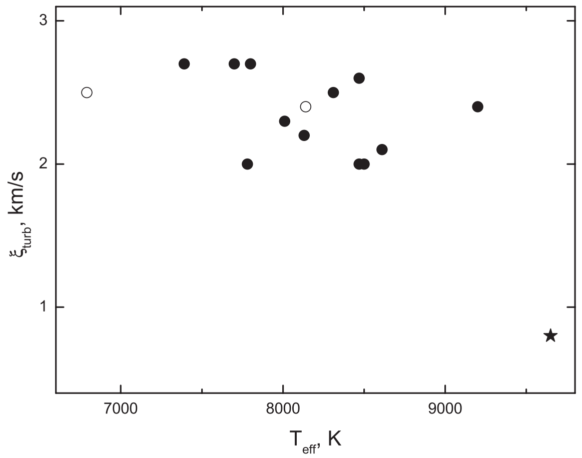

Figure 11. The dependence of the microturbulence on the effective temperature. The symbols are the same as in Fig. 5.

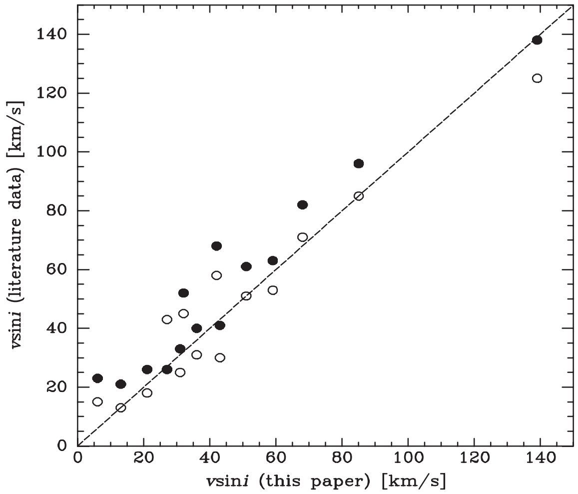

Figure 12. The projected rotational velocities obtained by us versus those given by Abt & Morrell (1995) (open circles) and by Royer et al. (2002) (filled circles).

of them, HD 155375, could be a new SB2 star based on five spectra obtained. The tidal interaction in all binary systems studied by us until now was explored. There is clear dependence of the Am peculiarity on the projected rotational velocity for clearly defined Am stars. Apart from that, there seems to be a correlation of Am peculiarity with eccentricity and perhaps also with orbital period and a weak anticorrelation with effective temperature.

Assuming that the Am peculiarity is due to microscopic diffusion processes in stable atmospheres, then this dependence of the Am peculiarity on the eccentricity must be due to some mechanism that will stabilize the atmosphere of the star and reduce mixing.

One could speculate that a star on an eccentric orbit is subject to a variable gravitational perturbation or oscillations. These might cause departures from single-star rotation, drive the star towards pseudo-synchronization and reduce the differential rotation and/or rotationally induced mixing.

This confirms the hypothesis of Budaj (1996, 1997) regarding the existence of a stabilization mechanism due to the companion of the star and the suggestion that this mechanism operates up to the orbital period of about 200 d and is relevant for the Am phenomenon.

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