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Orbits of new spectroscopic components in 7 multiple systems*

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Abstract. New close sub-systems are discovered in wide physical multiple stars. Elements of spectroscopic orbits are given for the components of quadruple systems ADS 1315C, 3608C, 3824C, 3991A and for the components of triple systems ADS 1849A, 6646A, 8861A. Physical parameters (magnitudes, spectral types, masses of individual components, distances to the systems, angular separations) are estimated by combining all available data. The nearby M dwarf ADS 8861A = Gliese 507A is a good candidate for speckle resolution. The very hot white dwarf discovered by Hodgkin et al. (1993) is likely to be an additional visual component to ADS 3824C, so this system may be quintuple; however, a search of $2^{\rm d}\!.993$ photometric periodicity possibly caused by the hot close companion is highly desirable.

Key words: binaries: spectroscopic — binaries: visual

1. Introduction

It is well known that the observational data on double and multiple stars suffer from severe incompleteness. Limitations of our observing techniques are not the only reason for it; yet another reason of incompleteness is that just a small fraction of systems was observed systematically by all relevant methods. This is particularly true with respect to radial velocities, as only stars brighter that $6^{\rm m}$ were observed spectroscopically in a more or less systematic way.

This is why I started in 1994 a program of radial velocity measurements of double and multiple stars, with particular emphasis on faint components. A couple of short-period orbits already resulted from this program (Tokovinin 1994; Tokovinin & Smekhov 1995). This paper presents another 7 orbits. These spectroscopic components were discovered independently; however, 2 of them have previously published indications of velocity variability, and one has a spectroscopic orbit (see discussion of individual systems below).

A correlation Radial-Velocity-Meter (RVM) (Tokovinin 1987) was used for the measurements. Observations were made mostly in 1994-1995 with the 70-cm telescope located on the Moscow University campus and with the 1-m telescope of the Simeis Observatory in Crimea. Velocity zero point was determined by observations of several IAU velocity standards each night. Some observations were also made by the author in 1994 with the CORAVEL spectrometer (Baranne et al. 1979) at the Haute Provence Observatory.

Table 1 contains the identification data on the 7 systems: IDS (1900) index, ADS number (Aitken 1932), HD or BD number, equatorial coordinates for 2000.0 and other identifiers, e.g. double star discoverer codes. The ADS number is a common identifier for all these systems and it will be used throughout this paper.

Basic data on system components (spectral types, visual magnitudes and $B-V$ colors) are given in the left columns of Table 2 and were collected from the literature or taken from SIMBAD. Most of the photometry is from Eggen (1963). The last 3 columns of Table 2 summarize the results of our study and contain the mean equivalent width (EW) of the cross-correlation (CC) dip with its error, the projected axial rotational velocity $V \sin i$ and its error (as found from the width of CC dip), and mean radial velocities (the velocity taken from literature is marked with asterisk). The method of $V \sin i$ determination and the dependence of EW on $B-V$ color and metallicity can be found in (Tokovinin 1990).

2. Spectroscopic orbits and system parameters

The final orbital elements were found by least-squares fitting with weights inversely proportional to the square of

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[*] Table 4 and Appendix are only available in electronic form at the CDS via anonymous ftp to:
cdsarc.u-strasbg.fr (130.79.128.5)
or via http://cdsweb.u-strasbg.fr/Abstract.html

Table 1. Object identification

IDS(1900)	ADS	HD/BD	R.A., Dec.(2000.0)	Other
$01347+4922$	1315	+49 435	$01^{\rm h}40^{\rm m}52^{\rm s}+49°52'55''$	Hu 531
$02213-1547$	1849	15144	$02^{\rm h}26^{\rm m}00^{\rm s}-15°20'28''$	HR 710, AB Cet
$04556+2631$	3608	32092/93	$05^{h}01^{m}44^{s}+26°40'14''$	A 1844
$05089+3234$	3824	33959	$05^{h}15^{m}24^{s}+32°41'16''$	HR 1706, KW Aur
$05188-0058$	3991	35317	$05^{h}23^{m}51^{s}-00°52'02''$	HR 1782
$08011+7948$	6646	67064	$08^{h}16^{m}32^{s}+79°30'06''$	STF 1169
$13149+3540$	8861	+35 2436	$13^{h}19^{m}34^{s}+35°07'15''$	Gliese 507AB

Table 2. Basic observational data

ADS	Comp.	Spectral type	V	$B-V$	EW, km/s	$V\sin i$, km/s	$V_{\rm r}$, km/s
1315	AB	K1V	9.73	0.83	2.87 ± 0.13	< 2.0	3.95 ± 0.21
	C		10.21	0.86	2.88 ± 0.15	11.3 ± 1.0	3.70 ± 0.36
1849	A	A6Vp	5.83	0.15	1.11 ± 0.02	9.4 ± 0.4	1.50 ± 0.10
	B		9.26	0.62	2.42 ± 0.13	<6.0	0.78 ± 0.19
3608	AB	G0V+G8V	6.74	0.48	1.70 ± 0.04	(8.8)	-6.75 ± 0.15
	C	G5	8.22	0.70			-7.50 ± 0.28
	Ca				2.19 ± 0.05	3.8 ± 0.8	-
	Cb				0.36 ± 0.12	-	-
3824	A	A9IV	5.02	0.23	-	-	-9.8 *
	C		7.95	0.41	1.65 ± 0.07	15.2 ± 0.8	-8.37 ± 0.51
3991	ABC	F7V	6.11	0.50	- -	- -	- -
	Aa				1.19 ± 0.03	6.9 ± 0.5	55.88 ± 0.35
	Ab				0.25 ± 0.02	-	-
	BC	F8V	7.00		1.84 ± 0.7	(13.3)	52.10 ± 0.19
6646	A	G0	8.4		1.67 ± 0.05	9.0 ± 0.6	-6.65 ± 0.22
	B	G0	9.2		2.00 ± 0.05	<4.8	-6.59 ± 0.13
8861	A	dM1.5	9.51	1.47	2.27 ± 0.10	-	-8.08 ± 0.18
	Aa				1.70 ± 0.06	8.2 ± 1.9	-
	Ab				0.76 ± 0.07	11.8 ± 2.9	-

formal velocity errors. The elements and their formal errors are given in Table 3. For circular orbits I checked that non-zero eccentricity did not result in the significant improvement of the quality of fit. Number of measurements used (primary and secondary lines counted separately) and the unweighted rms residuals are given in the 8th column of Table 3. Its last column contains mass function for single-lined systems or $M\sin^3 i$ for the components of double-lined systems. Radial velocity curves are given in the Figs. 1-7. Individual observations, their errors and residuals can be found in Table 4 which is available in electronic form only. It contains also the measurements of non-variable components. The CORAVEL measurements are marked as COR in the last column. The measurements rejected in orbit computation are marked by colons.

The reduction of the blended CC dips of double-lined systems ADS 3991 and 8861 was done in two steps. First, the average parameters of component's dips were determined from observations made at the moments of the greatest radial velocity difference. Then the width and contrast of individual dips were fixed and only velocities were fitted. This procedure works well even for radial velocity difference of few km/s.

Magnitude difference of the components of double-lined systems was determined by fitting simultaneously the ratio of dip equivalent widths EW and the combined $B-V$ color (Tokovinin 1990):

$$EW = \begin{cases} 0.08 + 4(B-V) & \text{for } B-V < 0.84 \\ 3.9 - 8.75[(B-V) - 1.07]^2 & \text{for } B-V > 0.84 \end{cases} \quad (1)$$

Table 3. Orbital elements

ADS	P, days	T JDH	e	ω °	K_1, K_2, km/s	γ, km/s	N σ	$f(m)$ $M\sin^3 i$
1315C	2.2220	49983.7855	0.0	0.0	28.63	3.70	11	0.00540
	± 0.0018	± 0.0048			± 0.59	± 0.36	0.84	± 0.00055
1849A	2.997812	49986.717	0.030	32.3	18.42	1.50	32	0.00194
	±0.000004	± 0.198	±0.009	±24.0	± 0.25	± 0.10	0.52	±0.00008
3608C	186.28	49712.2	0.343	193.7	18.35	-7.50	25	0.793
	±0.53	± 1.4	± 0.025	± 2.8	± 0.28	± 0.28	0.50	± 0.113
					25.65		2.50	0.567
					± 1.78			± 0.045
3824C	2.99340	49974.296	0.0	0.0	28.66	-8.98	19	0.00729
	± 0.00010	± 0.007			± 0.38	± 0.25	1.24	±0.00037
3991A	22.5804	49990.09	0.610	216.1	53.25	54.97	23	1.287
	± 0.0004	± 0.06	± 0.005	± 1.3	± 0.55	±0.24	2.05	± 0.038
					71.33		3.54	0.961
					± 1.03			± 0.021
6646A	4.88430	49419.616	0.0	0.0	39.14	-6.65	24	0.0303
	± 0.00014	± 0.008			± 0.29	± 0.22	0.95	±0.0007
8861A	200.26	48780.30	0.531	348.8	17.11	-8.08	52	0.375
	± 0.09	±0.42	± 0.011	±1.6	±0.21	±0.18	1.38	± 0.019
					20.73		2.81	0.309
					± 0.44			± 0.012

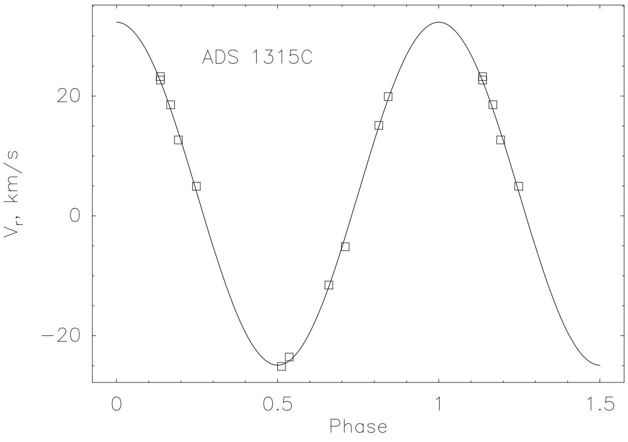

Fig. 1. Radial velocity curve of ADS 1315C

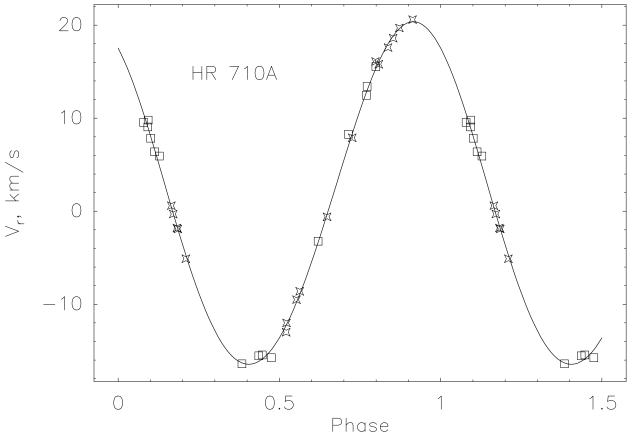

Fig. 2. Radial velocity curve of ADS 1849A = HR 710. Our measurements are plotted as squares, those of Bonsack (1981) as stars

It is also assumed that for main-sequence components the standard dependence of absolute magnitude M_V and mass on $B-V$ color holds. The interpolation formulas

$$M_V = 1.03 + 7.48(B-V) + 0.25x(x-6.667), \quad x = (1.75 - B + V)^{-1} \qquad (2)$$

$$\text{Mass} = 0.67 - 0.38y - 1.46y^3, \quad y = B - V - 1.125 \qquad (3)$$

were used. They offer a good approximation of the data given in the table B1 of Gray (1988) for spectral types from F5V to M2V.

Table 5. Models of multiple systems

ADS π, ″ $m-M$	Comp.	m_V	$B-V$	Sp. type	M_V	Mass, $M_\odot$	Sys.	Type	Period	a, ″
1315	A	10.26	0.83	K0V	5.52	0.82	AB-C	CPM	8000: y	6.1
0.0113	B	10.76	0.86	K1V	6.02	0.79	AB	VB	92.8 y	0.27
4.74 *d*	Ca	10.21	0.86	K0V	5.47	0.82	Cab	SB1	2.22 d	0.0004
	Cb	-	-	M	-	>0.18				
1849	Aa	5.83	0.15	A6Vp	1.1	1.8	AB	CPM	20000: y	12.0
0.0111	Ab	-	-	WD?	-	1.0 ?	Aab	SB1	3.00 d	0.0006
4.8 *s*	B	9.26	0.62	G2V	4.5	1.06				
3608	A	7.1	0.50	F7V	3.6	1.3	AB-C	CPM	130000: y	78.5
0.0199	B	8.4	0.65	G4V	4.9	1.0	AB	VB	25.0 y	0.225
3.5 *d*	Ca	8.34	0.67	G5V	4.8	0.98	Cab	SB2	186.3 d	0.015
	Cb	10.69	1.03	K5V	7.2	0.70				
3824	Aa	5.02	0.23	A9IV	0.2	1.8	AC	CPM	24000: y	14.3
0.0110	Ab	-	-	WD?	-	1.0:	Aab	SB1	3.79 d	0.0007
4.8 *s*	Ca	7.95	0.41	F5V	3.2	1.3	Cab	SB1	2.99 d	0.0005
	Cb	-	-	M3V	-	0.3 ?	CD	?	1000 ? y	0.5 ?
	D ?	14.1	-	DA	-	-				
3991	Aa	6.86	0.43	F5V	3.2	1.3	A-BC	CPM	800: y	2.7
0.0184	Ab	9.14	0.74	G5V	5.4	0.9	Aab	SB2	22.6 d	0.0038
3.7 *d*	B	7.60	0.53	F8V	3.8	1.2	BC	VB	49.4 y	0.332
	C	7.93	0.58	F8V	4.2	1.1				
6646	Aa	8.5	0.40	F4V:	3.0	1.4	AB	CPM	76000: y	20.7
0.0079	Ab	-	-	M	-	>0.47	Aab	SB1	4.88 d	0.0005
5.5 *s*	B	9.2	0.48	F7V:	3.6	1.3				
8861	Aa	10.02	1.45	M1V	9.11	0.48	AB	CPM	2800: y	17.0
0.0657	Ab	10.57	1.51	M2V	9.66	0.40	Aab	SB2	200.2 d	0.051
0.91 *s*	B	12.09	1.59	M3V	11.18	0.35				

Distance to a multiple system is one of the most important parameters in interpretation and modelling of observations. Generally, the distances to multiple systems can be determined with better accuracy than distances to single stars because different data can be combined. Three systems contain visual binaries with known orbits. Masses of their components are estimated from spectral types and dynamical parallaxes are calculated. For the remaining systems less secure photometric distances are adopted.

The models of multiple systems are given in Table 5. First column contains ADS numbers, parallaxes and distance moduli $m-M$ (d stands for dynamical distances, s for spectroscopic). Second column gives component identification (visual components are marked by upper-case letters, spectroscopic components by second lower-case letters). Then in Cols. 3 to 7 the estimated visual magnitudes, spectral types, absolute magnitudes and masses of components are given. These estimates come from the magnitude differences of double-lined systems and from spectral type assignments that would match absolute magnitude, observed colors and equivalent widths. Thus the data in the left half of Table 5 represent an "educated guess" based on the available observational data, rather than directly measured quantities. Lower limits of secondary mass are given for single-lined systems.

Each hierarchical multiple system can be decomposed into a number of binary systems. The last four columns of Table 5 summarize the parameters of these "elementary" binaries. Column "type" has obvious coding: CPM for common proper motion pairs, VB for visual binaries with known orbit, SB1 and SB2 for single- and double-lined spectroscopic binaries. The periods of CPM pairs are estimated by the third Kepler law from separation a

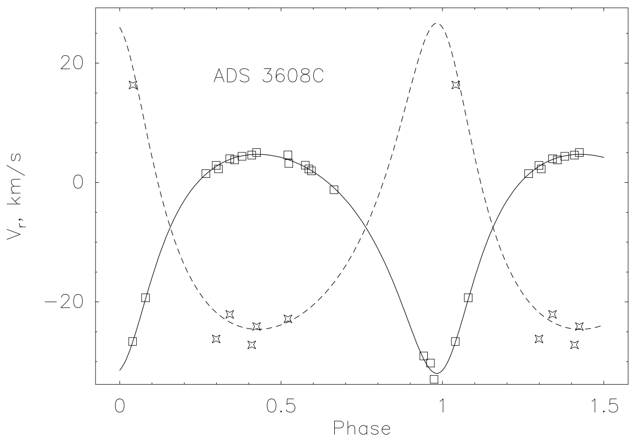

Fig. 3. Radial velocity curve of ADS 3608C. Solid line and squares refer to the primary component, dashed line and stars refer to the secondary component

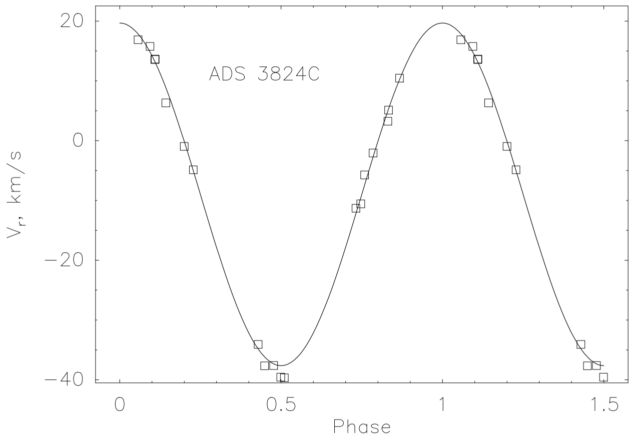

Fig. 4. Radial velocity curve of ADS 3824C = HR 1706C

(given in the last column), parallax π and total mass in solar mass units:

$$P = (a/\pi)^{3/2}\ \mathrm{Mass}^{-1/2}, \tag{4}$$

where P is in years, a and π in arcseconds. The same formula is inverted to calculate apparent semimajor axis of a spectroscopic binary from its period. The radial velocity difference $K_1 + K_2$ in km/s between the components of a visual binary is estimated by the formula

$$K_1 + K_2 = 29.78\ \mathrm{Mass}^{-1/3}\ P^{-1/3}\ \sin i\ (1 - \mathrm{e}^2)^{-1/2} \tag{5}$$

where P is in years. When estimating the expected radial velocity difference between CPM components the terms containing inclination i and eccentricity e are omitted from Eq. (5) because they are not known.

Discussion of individual systems is given in the Appendix.

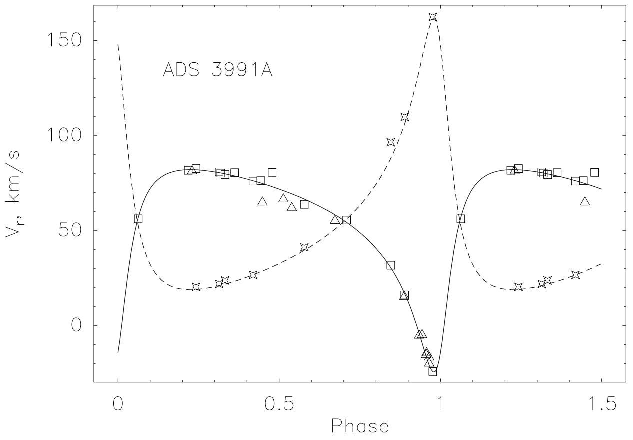

Fig. 5. Radial velocity curve of ADS 3991A. Our measurements of primary and secondary components are plotted as squares and stars, respectively. Data of Beavers & Eitter (1986) for the primary are plotted as triangles

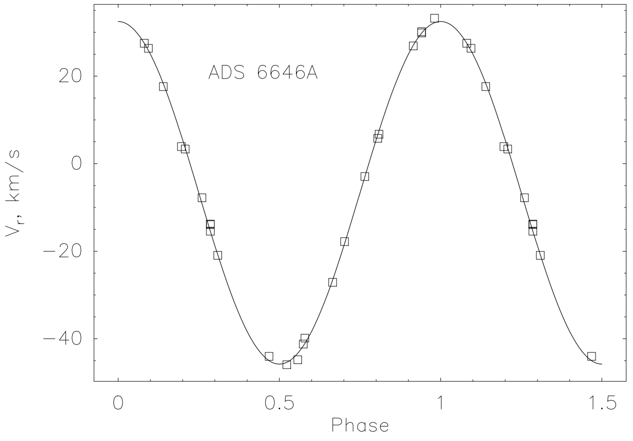

Fig. 6. Radial velocity curve of ADS 6646A

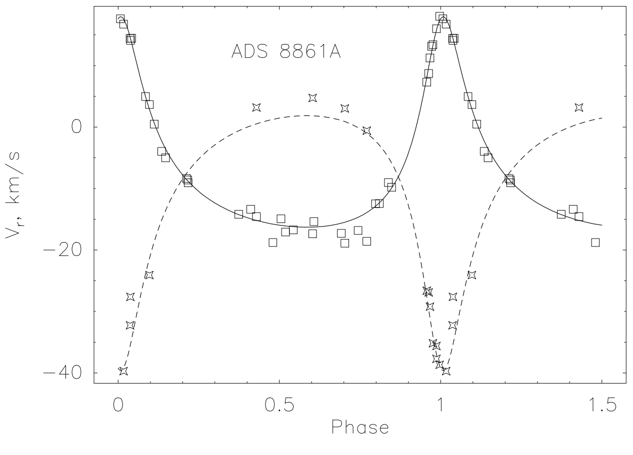

Fig. 7. Radial velocity curve of ADS 8861A = Gliese 507A

3. Conclusion

It is shown that the systems ADS 1315, 3608, 3824 and 3991 are not triple but quadruple. The two new triple systems are ADS 6646 and 8861. The spectroscopic orbit of ADS 1849A is recalculated using new data. Radial velocity measurements indicate that there are no other close spectroscopic components in these systems (with possible exception of ADS 8861B), and current knowledge of system composition is complete. Even if there are faint undetected visual components, their possible orbital parameters are severely constrained by radial velocity data and the availability of empty hierarchical levels. So, this study can be considered as a step towards the definition of a new sample of systems with known degree of multiplicity.

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