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Statistics of spectroscopic sub-systems in visual multiple stars*

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Abstract. A large sample of visual multiples of spectral types F5-M has been surveyed for the presence of spectroscopic sub-systems. Some 4200 radial velocities of 574 components were measured in 1994–2000 with the correlation radial velocity meter. A total of 46 new spectroscopic orbits were computed for this sample. Physical relations are established for most of the visual systems and several optical components are identified as well. The period distribution of sub-systems has a maximum at periods from 2 to 7 days, likely explained by a combination of tidal dissipation with triple-star dynamics. The fraction of spectroscopic sub-systems among the dwarf components of close visual binaries with known orbits is similar to that of field dwarfs, from 11% to 18% per component. Sub-systems are more frequent among the components of wide visual binaries and among wide tertiary components to the known visual or spectroscopic binaries – 20% and 30%, respectively. In triple systems with both outer (visual) and inner (spectroscopic) orbits known, we find an anti-correlation between the periods of inner sub-systems and the eccentricities of outer orbits which must be related to dynamical stability constraints.

Key words. binaries: spectroscopic – binaries: visual

1. Introduction

Formation of binary and multiple stars still remains a puzzle. When it is solved, i.e. when the major physical ingredients are identified and modeled, an important part of the general star formation picture will be clarified. The origin of close binaries is particularly difficult to explain, their orbit size being less than the sum of component radii at birth. Evidently, the orbits must shrink as their components evolve towards the Main Sequence, but the mechanism by which angular momentum and orbital energy are lost is yet unknown. Batten (1973) suggested that study of multiple stars might give a key to understanding binary formation. Fekel (1981) made a first serious step towards systematic analysis of observational data on close triple stars, although the number of systems known at that time was small.

In 1994 we started a program of radial velocity measurements of the components of visual double and multiple stars, related to the compilation of the Multiple Star Catalogue (MSC) (Tokovinin 1997b). The aims of this program were:

- to establish whether the visual systems are physical or optical;
- to discover new spectroscopic sub-systems, complementing the knowledge of stellar multiplicity and its statistics.

The emphasis of A.T.'s program was made on the resolved components (separation $>1''$) with no previous data on radial velocities, while M.S. observed mostly unresolved visual binaries with known orbits to determine the frequency of close sub-systems.

Precise measurement of the radial velocity difference between the components of long-period visual pairs was required for the computation of orbits by the dynamical method of Kiselev & Kiyaeva (1980). Initial results of such measurements, started in 1986, were published in Tokovinin (1994a); data on additional objects are given here. In some pairs from the Kiselev program the spectroscopic sub-systems were discovered and they were included in MSC. So, both observing programs overlap and are considered here jointly.

In Sect. 2 the information on observations is given. Main data tables are described in Sect. 3. The analysis is done in Sect. 4, where three statistically "clean"

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* Tables 1, 2, and 6 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/cgi-bin/qcat?J/A+A/382/118

sub-samples are isolated from the general data. Section 5 contains conclusions and discussion.

2. Observations

A correlation Radial Velocity Meter (RVM) (Tokovinin 1987) was used for the measurements. Observations were made in 1994–2000 at the 1-m telescope of the Simeis Observatory in Crimea and at the 70-cm telescope located on the Moscow University campus in Moscow. Velocity zero point was determined by observations of several IAU velocity standards each night. Some observations were also made by A.T. in September 1994 with the CORAVEL spectrometer (Baranne et al. 1979) at the Haute Provence Observatory. The components of spectral type later than F5 and brighter than $V = 11$ are accessible to these instruments.

Data processing, estimation of the measurement errors and their analysis are described in (Tokovinin 1992, 1997a). Briefly, internal error of each measurement is estimated as $\sigma_{\rm i}^2 = \sigma_{\rm fit}^2 + \sigma_0^2$, where $\sigma_{\rm fit}$ is the formal error of fitting a Gaussian curve to the observed correlation dip and $\sigma_0 = 0.3$ km s^{-1} is the additional instrumental error found from the scatter of standard star measurements. Average velocities are computed with weights proportional to $\sigma_{\rm i}^{-2}$, the scatter of data around these averages gives an estimate of external errors $\sigma_{\rm e}$.

Measurement of the radial velocities of visual multiple stars involves specific problems related to the proximity of other visual companions. For separations from $0\farcs5$ to $5''$ the light of the visual components can be mixed in the slit in a variable proportion which depends on seeing, slit orientation and guiding. In some instances the RVM was turned in position angle to make the slit perpendicular to the components; this may have caused small changes of zero point owing to a possible shift of the light path in the spectrograph. In short, the quality of the radial velocities of partially resolved double stars is somewhat lower than the standard quality of RVM data. For these reasons the formal analysis of velocity variability by the $P(\chi^2)$ statistics was supplemented by manual data inspection.

3. Data overview

In Table 1 the object identifications, mean velocities and their interpretation are given for the 574 individual components or unresolved combinations of components.

Each object is identified, first, by its WDS-style coordinates J2000. Then component(s) are listed as given in the WDS (Worley & Douglass 1997), followed by HD number (or BD, when HD is missing). When a secondary component has a HD number different from that of the primary, this number is listed; otherwise, a BD identifier (if different from primary) is listed; finally, the HD or BD for primary are duplicated for secondary if the latter has no separate identifiers in these catalogues. When a Hipparcos number of a secondary is different from that of a primary, this is indicated in the Notes. The third identifier is the number in ADS catalogue (Aitken 1932).

The weighted mean radial velocities, their errors (the largest of the internal and external errors of the mean computed from $\sigma_{\rm i}$ and $\sigma_{\rm e}$), numbers of measurements N and the probabilities $P(\chi^2)$ that the velocity is constant (or, more precisely, the probabilities of $\chi^2(N)$ to exceed the actual χ^2 values) are given. Table 1 also contains the parameters derived from the shape of correlation dip: mean equivalent widths EW and their errors in km s^{-1}, the numbers of measurements used in the averaging (noisy dips were excluded), the projected rotation velocities $V \sin i$, their errors in km s^{-1} and flags (asterisks) signalling that an upper limit of $V \sin i$ is given instead of its error. The calibration of these parameters for RVM is discussed in Tokovinin (1990).

In the last columns of Table 1 some interpretation of the data is provided. First, the variability of the radial velocity is summarized by evident codes (C for constant, V for variable velocity, S1O and S2O for single- and double-lined spectroscopic binaries with computed orbits). Asterisk indicates cases when proximity of other components could have affected the quality of measurements, as explained above. In general, variable components have total velocity range over 2 km s^{-1}. In many cases the comparison with other components of the same system helps: a large velocity difference alerts to the possible spectroscopic sub-systems while similar velocities strengthen the conclusion on constant velocity.

The physical relationship between components as derived from radial velocities is coded as follows: asterisk for primary components, P for physical, and O for optical secondary components. In the majority of cases these conclusions are corroborated by relative astrometry and/or photometry of the components (see more details in MSC). Then letter R follows to indicate that individual measurements are published in Table 2. Finally, letters T, D or B stand for the components included in the three statistical samples discussed in Sect. 4.2. Notes to Table 1 contain short comments on individual objects and additional identifications.

Most of individual radial velocities (2483 observations of 499 components) are published here in Table 2. We omit only the objects whose velocities have already been published together with orbits and few spectroscopic binaries with yet unknown orbits where the measured velocities are subject to further interpretation (e.g. dip splitting into components, etc.). In Table 2 the components are identified only by WDS codes and letters, followed by heliocentric Julian dates (minus 2 400 000), radial velocities and their internal errors $\sigma_{\rm fit}$ as found from dip fitting. A letter C in the last column marks the 25 CORAVEL measurements.

The summary of 46 published orbits which resulted from this program is given in Table 3. In Sect. 4 we analyze their period distribution. Then the fraction of spectroscopic binaries in three sub-samples will be estimated and compared to other populations. Finally, we focus our

Table 3. Summary of new spectroscopic orbits (R = references).

WDS(2000)	HD/BD		P, d	e	R
00063+5826 AB	123	SB1	47.51	0.42	a
00134+2659 C	895	SB2	6.03	0.03	b
00271−0753 B	2333	SB1	6.39	0.00	c
00328+2817 B	2942	SB2	7.49	0.06	d
00360+3000 A	3266	SB2	36.00	0.45	d
01256+3133 C	8624	SB2	14.91	0.13	d
01409+4953 C	+49 435	SB1	2.22	0.00	e
01413+2545 B	10308	SB1	1.44	0.00	b
02260−1520 A	15144	SB1	3.00	0.00	e
03344+2428 C	22091	SB2	3.75	0.00	b
03368+0035 B	22468	SB1	1152	0.40	a
03470+4126 B	23439	SB1	48.65	0.67	f
04226+2538 Ba	27638	SB2	17.60	0.30	a
04226+2538 Bc	27638	SB1	2951	0.26	a
04289+3021 A	28271	SB1	460.7	0.31	a
04290+1610 B	28363	SB1	21.25	0.27	c
04356+1010 B	29140	SB1	1350	0.66	a
05017+2640 C	32093	SB2	186.28	0.34	e
05154+3242 C	33959	SB1	2.99	0.00	e
05239−0052 A	35317	SB2	22.58	0.61	e
05364+2200 A	37013	SB1	49.38	0.10	g
06481+5542 B	48766	SB1	4.26	0.00	d
08165+7930 A	67064	SB1	4.88	0.00	e
09353+3958 B	82767	SB1	28.23	0.44	b
10437+4612 B	92855	SB1	5.61	0.32	h
11366+5608 B	+56 1529	SB2	1690.15	0.65	d
13192+3507 A	+35 243	SB2	200.26	0.53	e
14130+5519 A	124640	SB1	1047.80	0.75	i
14563+2928 A	132049	SB1	3237.70	0.15	d
15382+3615 A	139691	SB2	3.27	0.00	j
15382+3615 D	139691	SB1	14.19	0.31	j
15387−0848 A	139461	SB1	887.66	0.92	a
16242+3702 A	148086	SB1	21.59	0.03	d
17394−1546 A	160239	SB1	6.92	0.04	k
18002+8000 A	166866	SB2	1247.80	0.98	l
18002+8000 B	166865	SB2	10.53	0.38	l
18015+8436 AB	+84 409	SB1	4.64	0.00	d
18238+5139 B	169816	SB1	126.38	0.33	a
18240+5848 C	238865	SB1	2.71	0.00	m
18537−0533 A	175039	SB1	50.51	0.59	k
19062+3026 A	178091	SB2	27.25	0.34	n
19091+3436 A	178911	SB2	1294.60	0.59	o
19111+3847 C	179484	SB1	522.7	0.61	a
19351+5038 A	185082	SB1	39.62	0.50	g
20078+0924 B	191104	SB2	23.84	0.12	b
22362+7253 A	214511	SB1	4.57	0.03	b

References (R): a – Tokovinin & Gorynya (2001); b – Tokovinin (1998); c – Smekhov (1995); d – Tokovinin (1999a); e – Tokovinin (1997a); f – Tokovinin et al. (1994); g – Smekhov (1999); h – Tokovinin (1994b); i – Kiyaeva et al. (1998); j – Tokovinin et al. (1998); k – Smekhov (2002); l – Tokovinin (1995); m – Tokovinin & Smekhov (1995); n – Smekhov (1994); o – Tokovinin et al. (2000).

attention on binaries with both visual and spectroscopic orbits known and study the correlations between the elements of inner and outer orbits.

4. Statistics of spectroscopic sub-systems

4.1. Distribution of periods

The period distribution of binary G dwarfs slowly rizses with increasing $\log P$ (Duquennoy & Mayor 1991, hereafter DM91). The distribution of periods in spectroscopic sub-systems is different. In Fig. 1 the distribution of dwarf spectroscopic sub-systems with primary mass less than 1.5 $M_\odot$ in the current version of MSC is traced in a full line, and the period distribution of the objects from Table 3 (excluding two optical systems) – in a dashed line. A characteristic of both distributions is a sharp drop in the number of systems at periods longer than 7 days (bin limits are adjusted to accentuate this feature). The drop at $P_S > 7^d$ was noted in Tokovinin (1997b) and tentatively explained by selection. However, we see now that this effect is not due to selection, because sub-systems with $P_S > 7^d$ are in fact easy to discover.

A period distribution with a peak around 2–7 days is also found for dwarf binaries in the Hyades (Fig. 8b in DM91). García & Mermilliod (2001) noted that the periods of massive O-type spectroscopic binaries in several open clusters have a remarkable excess around 3^d, and that many of these spectroscopic systems are members of higher-order hierarchical multiples.

This feature in the period distribution seems to indicate the importance of tidal dissipation. In dwarf binaries, tides circularize the orbits with periods shorter than ∼8 days (Zahn & Bouchet 1989), which matches the right limit of the peak in Fig. 1. Close binaries with periods of few days may be formed by tidal capture, likely to happen in unstable (chaotic) multiple systems and in dense clusters (Mardling & Aarseth 2001). Even in stable hierarchical triples a distant companion perturbs the inner orbit and can make it very eccentric if the initial relative angle ϕ between inner and outer orbits is high. This effect, known as Kozai cycle, operates when inner orbit does not experience additional apsidal rotation caused by tides. So, when the periastron distance in the inner orbit becomes small and the components start to interact tidally, the Kozai cycle breaks. The inner orbit is subsequently circularized by the tides. Kiseleva et al. (1998) were able to explain the formation of the close inner binary in Algol by such process.

Eccentricities of inner orbits are increased by the Kozai mechanism only if $\phi > 39°$ (Holman et al. 1997). If initially the relative orientation of inner and outer orbits is random, $\cos\phi$ is uniformly distributed between 0 and 1. Hence, the fraction of multiples that do not experience Kiseleva-Kozai effect is $\cos 39° = 0.22$. In fact it is larger because the relative orbit orientation is not random (Tokovinin 1997b). Looking at Fig. 1, we see that the number of systems with $P_S > 7^d$ drops by ∼2 times, hence no more than half of the triple systems may have undergone tidal shrinkage of inner orbits.

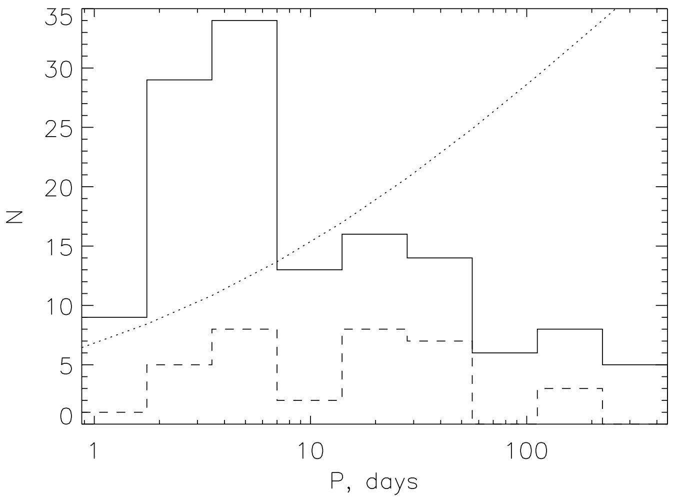

Fig. 1. Histogram of the periods of spectroscopic sub-systems in the MSC (full line), including this survey (dashed line). The bin size is two times the period. The doted line shows the model of period distribution in the G-dwarf sample of DM91.

The impact of our program on the general data on low-mass multiple stars can be inferred from Fig. 1. We contributed 22% of orbits in the period range 1.75^{d}–7^{d} and 57% in the range 14^{d}–56^{d}; longer periods were, evidently, less well surveyed by our predecessors. We expect that in most of sub-systems with yet unknown orbits the periods are also long.

4.2. Fraction of spectroscopic binaries in three samples

Our observational data are rather heterogeneous. In order to get meaningful statistical results, we isolated three "clean" sub-samples that were observed well enough: at least 3 observations with a time span of 300 days or more. This ensures good probability of detecting velocity variations for orbital periods up to 2–3 years. We exclude all evolved components and consider here only dwarfs of spectral types F5V and later. These samples are marked by the flags B, D, and T in Table 1. Distribution of variability status in each sample is given in Table 4.

Sample B consists of visual binaries with known orbits from the Fourth Catalog of visual orbits (Worley & Heintz 1983). We selected all systems north of declination $-15°$ with dwarf primaries of spectral types later that F5 and magnitude brighter than $10^{m}.6$. A total of 398 systems satisfy these criteria; 21 of them already contain known spectroscopic sub-systems and were excluded from our observing list. For 282 binaries we were able to obtain at least one observation, but only 177 are well observed and included in sample B. Among the 37 suspected variables there are 10 stars with slow velocity trends likely caused by their motion in visual orbits (flag VO in Table 1), while others may contain sub-systems. To be conservative, we do not take uncertain variables into consideration and estimate the minimum frequency of sub-systems in sample B as $31/177 = 0.18 \pm 0.03$. Here each binary system is counted as one; in 7 systems where both components were resolved, only the one with most variable velocity was counted (e.g. first 2 lines in Table 1). Counting additional 27 uncertain velocity variables, we obtain the maximum sub-system fraction of $58/177 = 0.33 \pm 0.04$.

Table 4. Radial velocity variablity in three samples.

Sample	N	Variability status				
		C	C?	V?	V	SBO
B: visual orbits	177	85	24	37	20	11
D: wide doubles	52	33	6	1	3	9
T: tertiaries	59	32	6	3	6	12

Now we correct for the bias caused by excluding the 21 known sub-systems. The number of objects not studied well enough is $398 - 21 - 177 = 200$. Supposing that 18% to 33% of them also contain additional sub-systems, we expect from 88 to 145 sub-systems in the whole sample, or a binary fraction of 22% to 36%. Petrie & Batten (1965) observed radial velocities of 234 resolved visual binaries and suggested that 35% of them contain spectroscopic sub-systems, although Batten (1973) feels that it was an over-estimate and that the real fraction must be close to 30%.

Both components of unresolved visual binaries have comparable brightness (by discovery selection), hence it is reasonable to assume that any of them can contain a spectroscopically detectable sub-system. It means that the fraction of spectroscopic sub-systems *per component* is only 11% to 18%.

Sample D consists of 52 components of 26 resolved visual binary stars, not known before to be spectroscopic binaries. Here the sub-system rate is $12/52 = 0.20 \pm 0.06$ per component.

Sample T consists of 59 apparently single dwarf tertiary components. Only physical components to the previously known pairs (either visual or spectroscopic) of spectral types later than F5V were selected. The total fraction of spectroscopic binaries is $18/59 = 0.30 \pm 0.07$.
In Table 5 the fraction of spectroscopic binaries with periods less than 100 and 1000 days is given for the three samples presented above. Our estimate for sample B remains tentative owing to a large number of systems with yet unknown orbits (we supposed that they have periods below 1000 days). In sample D, we assume that one system with unknown orbit (ADS 16111B) contributes to the 100–1000 day bin. For sample T, we estimate that of the 6 certain variables without orbits, three contribute to the $<100^{d}$ bin and one to 100^{d}–1000^{d} bin.

The spectroscopic binarity of the visual components is compared to that of field G-dwarfs as derived by DM91 and with the dwarf stars in two open clusters. The size N of all samples is small, leading to large uncertainties on the binary fractions. The fraction of spectroscopic binaries among tertiary components is seen to be $\sim$1.6 times

Table 5. Frequency of spectroscopic systems (percent).

Sample	N	$P < 100^d$	$P < 1000^d$	Ref.
Visual orbits (B)	177	-	11–18	a
Wide doubles (D)	56	10 ± 5	17 ± 6	a
Tertiaries (T)	59	20 ± 6	24 ± 6	a
G-dwarfs, field	166	8 ± 2	13 ± 3	b
Pleiades	88	9 ± 3	13 ± 4	c
Praesepe	80	16 ± 5	20 ± 5	d

References: a – this work; b – Duquennoy & Mayor (1991); c – Mermilliod et al. (1992); d – Mermilliod & Mayor (1999).

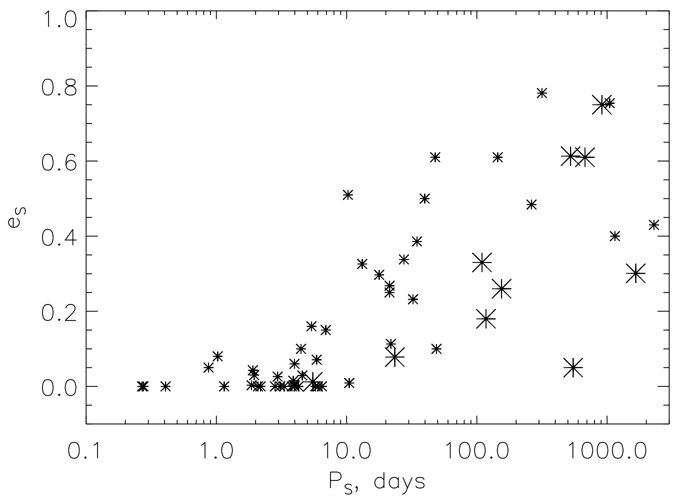

Fig. 2. Eccentricity of short-period sub-systems e_S versus their period P_S. Large symbols denote triples with period ratio $P_L/P_S < 100$, small symbols – other more hierarchical triples.

higher than among the field dwarfs or members of Pleiades cluster, but similar to the binary fraction in the Praesepe cluster. On the other hand, components of close visual double stars seem to have normal frequency of spectroscopic sub-systems. This difference between wide and close visual binaries may be related to dynamical stability of multiple systems (Sect. 5).

4.3. Visual+spectroscopic triples

Multiple systems with *both* outer (visual) and inner (spectroscopic) orbits known are important, permitting one to study various correlations between orbital elements, orbit coplanarity, etc. (Batten 1973). However, it is often difficult to derive spectroscopic orbits owing to line blending in the spectra of spatially unresolved triple systems: in our sample B, only 11 orbits out of 31 are computed. Here we use all available data on such systems for statistical analysis. In the current version of MSC, there are 138 visual+spectroscopic triples with both orbits known, from which we retain 65 systems with dwarf components of spectral type F5V or later (Table 6).

In Fig. 2 the period-eccentricity relation for spectroscopic sub-systems is plotted. Like dwarf binaries in the field, closer pairs have more circular orbits. However, at least half of the systems with periods below 8^d have eccentric orbits, while for field dwarfs with convective zones (later than F5V) all such orbits are circular (see discussion in Zahn & Bouchet 1989). Despite tidal dissipation tending to circularize inner orbits, non-zero eccentricity is maintained by the dynamical action of a third body. Eccentric short-period orbits may even serve to predict the existence of a third body (Mazeh 1990).

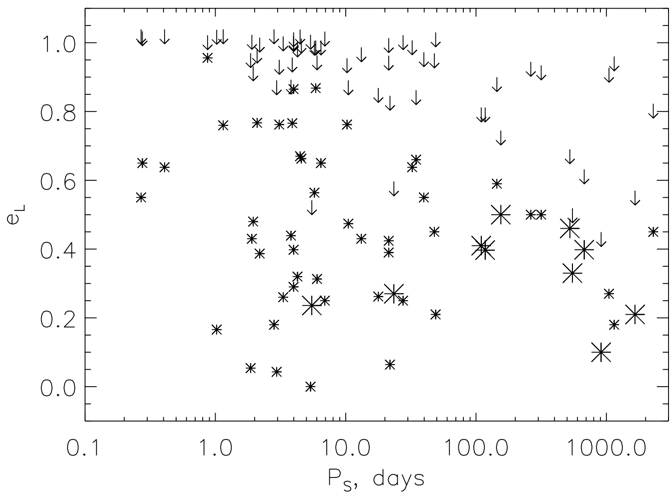

Fig. 3. Eccentricity of outer visual orbits e_L versus periods of spectroscopic sub-systems P_S. Arrows show the upper limits e_L^* from dynamical stability constraint Eq. (1).

In Fig. 3 we show an anti-correlation between the eccentricities of the outer (visual) orbits and the periods of inner sub-systems. Visual binaries which contain *close* sub-systems can have large e_L, while for $P_S > 100^d$ the eccentricities of outer orbits are only moderate, $e_L < 0.6$.

If period ratio P_L/P_S in a triple system is not very large, eccentricity of outer system is bounded by dynamical stability constraints. The approximate stability criterium of Eggleton & Kiseleva (1995) was recently revised by Mardling & Aarseth (2001). Their Eq. (90) can be recast in the form

$$(1 - e_L^*)^{6/5} = 2.8(1 + q_{\rm out})^{1/15}(P_S/P_L)^{2/3}(1 + e_L^*)^{2/5}, \quad (1)$$

where e_L^* is the critical eccentricity of the outer orbit. The dependence on mass ratio in outer system $q_{\rm out}$ is weak, we assumed $q_{\rm out} = 0.67$. The limiting eccentricities were computed for each system by solving Eq. (1) and are over-plotted in Fig. 3. Indeed, for long inner periods ($P_S > 100^d$), the stability limit is important and can explain why only triples with moderate e_L have survived. All systems are stable, although some are quite close to the limit (we note however that the elements of some long-period visual orbits are uncertain). Our finding on moderate eccentricities of outer orbits matches the results of Shatsky (2001) who reached the same conclusion for wide visual multiples from a statistical analysis of their relative motions.

5. Conclusions and discussion

Statistical analysis of spectroscopic sub-systems in multiple stars with dwarf low-mass primary components leads to the following conclusions:

1. There is a real excess of sub-systems with periods from 2 to 7 days, compared to longer periods. This peak in the period distribution is interpreted as a signature of tidal dissipation which, coupled with triple-star dynamics, makes the orbits of inner systems of shrink.
2. The frequency of spectroscopic sub-systems among wide tertiary components is increased in comparison with field dwarf population, whereas in closer visual binaries with known orbits it is similar to the field.
3. The eccentricities of outer orbits in multiple stars are anti-correlated with periods of inner sub-systems – a fact that can be explained by dynamical stability constraints.

The results presented above show that there exists a relation between short- and long-period binaries. The formation of a close binary is assisted by the presence of a remote companion which evacuates angular momentum from the inner system. The energy of orbital motion in the inner system could then be dissipated by tides. Reipurth (2000) suggested another scenario where a tertiary component stimulates accretion onto an inner binary, causing orbit shrinkage accompanied by jets. Thus, a triple system which could be unstable or marginally stable evolves into a stable one with shorter inner period. This mechanism also leads to the formation of close binaries. It was already noted (Mazeh 1990; Tokovinin 1997c) that a large fraction (if not all) of close dwarf spectroscopic binaries indeed have more distant tertiary components.

The eccentricities of outer orbits are influenced by dynamical stability: apparently, all instable multiples have disintegrated. The range of inner periods allowed by stability constraints is smaller in close visual multiples than in wide ones. This can explain, at least qualitatively, why the fraction of spectroscopic sub-systems in our sample B is lower than in samples D and T.

Advances in understanding the formation of multiple stars made in this study are more than modest compared to the immensity of the task. They do show however that statistics can bring important insights and that further accumulation of data is worth the effort. Studies of larger multiple-star samples of different environment and age are one evident direction of future research. Also, application of modern high-angular-resolution techniques looks promising for the study of the relative orientation of inner and outer orbital planes in multiple stars in order to constrain the formation theories. Many spectroscopic sub-systems discovered by us are candidates for these future observations.

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