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On the origin of binaries with twin components

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Abstract. The existence of a statistically significant excess of dwarf binaries with mass ratios from 0.95 to 1, as first noted by Lucy & Ricco (1979), is confirmed by modern data. Excess of such binaries, called twins, is found only for periods shorter than 40 days, and in the $2-30$ days period range they constitute 10–20% of the total binary population. Twins must have been formed by a special mechanism. It cannot be a mass transfer in contact pre-main-sequence binaries, fission is also unlikely. As shown by Bate (2000), accretion onto a close binary shifts mass ratio towards 1, so twins may originate from binaries that became close while still surrounded by massive envelopes. Many twins are members of higher-multiplicity systems and/or clusters, which probably explains an early formation of a close binary by stellar dynamics.

Key words: stars: binaries: close – stars: binaries: general – stars: formation

1. Introduction

The statistics of orbital parameters of binary and multiple stars is related to the mechanisms of their formation. Most informative in this respect are period P, eccentricity e, and mass ratio $q = M_2/M_1$ (q is defined here to be always less than 1). In this note we discuss the overabundance of dwarf binaries with very similar (twin) components in a specific period range.

Lucy & Ricco (1979, hereafter LR79) were the first to draw attention to the excess of spectroscopic binaries with nearly identical components. They "deconvolved" the observed mass ratio distribution from measurement errors, have shown that the peak at $q = 1$ is sharp, highly significant, and can not be attributed to selection effects. The $q = 1$ peak was not prominent only for the most massive OB binaries, but it was clearly apparent for the less massive main sequence detached binaries, from B9V to M, and seemed to increase towards smaller masses. Lucy & Ricco stated that this peak was a signature of a special binary formation mechanism which tends to produce identical components, they tentatively identified this mechanism with ring fragmentation.

Quite independently of the spectroscopic binary statistics, the frequent occurrence of binary stars with nearly equal components was evoked to explain the existence of the so-called "binary sequence" in the color-magnitude diagrams of open clusters. Binary sequence is composed of the stars that lie some 0.75 mag. above the cluster main sequence. It was recently discussed by Mermillod & Mayor (1999) for Praesepe and by Kähler (1999) for Pleiades. However, Hurley & Tout (1998) have shown that even for uniformly distributed mass ratio the binary sequence may appear.

The study of the distribution of binary star mass ratio has a long history. A bimodal distribution of q for spectroscopic binaries, with peaks at $q \approx 0.25$ and $q \approx 1$, was found by some authors and later contested by others. Relevant papers were reviewed by Trimble (1990), Batten (1992) and Duquennoy & Mayor (1991, hereafter DM91).

In the past twenty years the paper LR79 was cited only occasionally. The purpose of our study is to reconsider the $q = 1$ peak using modern data and to discuss its possible origin.

2. Mass ratio statistics

We investigate here the solar-type binaries, or, more precisely, the spectroscopic binaries with dwarf primaries between 0.8 and 1.3 $M_\odot$. These limits correspond to spectral types from K0V to F5V, or to B$-$V colors from 0.82 to 0.45. These stars have small axial rotation and numerous sharp lines, which facilitates the radial velocity measurements. Correlation radial velocity spectrometers are very successful in detecting and study of such binaries, and in fact have contributed most of the known orbits. The binary sequence in open clusters is manifested most clearly in the same mass range.

Here we study a portion of the mass ratio distribution for $q > 0.8$ and consider only double-lined binaries (SB2). In this range detection of secondary lines is fairly complete and there are little remaining selection effects (LR79). Thus our task is much simpler than the study of the overall q distribution (e.g. Mazeh et al. 1992, Tokovinin 1992). Much of the controversy relating to the $q = 1$ peak in the overall q distribution (e.g. the relative proportion of SB2 and SB1 in volume-limited samples and in catalogues) does not relate to the sharp feature of q distribution discussed here.

Spectroscopic binaries with nearly identical components are found among all spectral types. For example, Batten (1992)

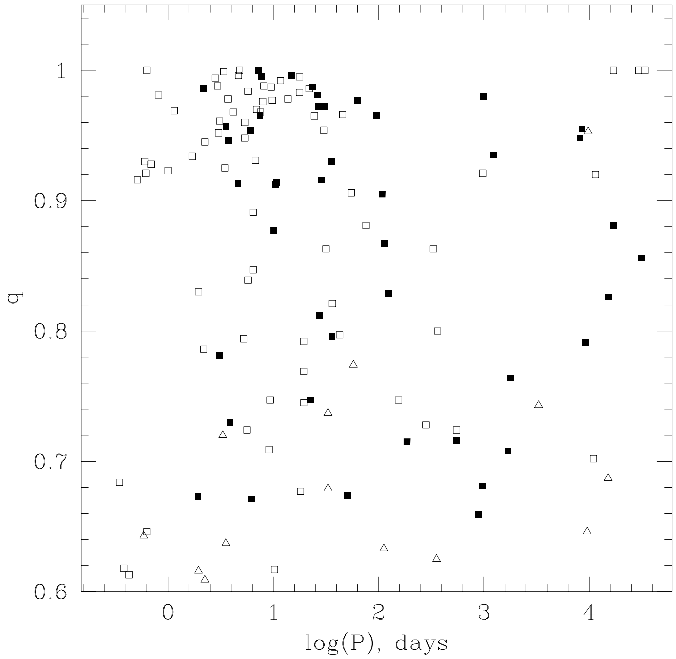

Fig. 1. Mass ratio of solar-type double-lined spectroscopic binaries is plotted against the logarithm of their orbital period in days. Empty squares - data from the Batten et al. (1989) catalogue, filled squares - recent orbits (SB+). Triangles show the lower mass ratio limits for single-lined binaries from Batten et al. (1989).

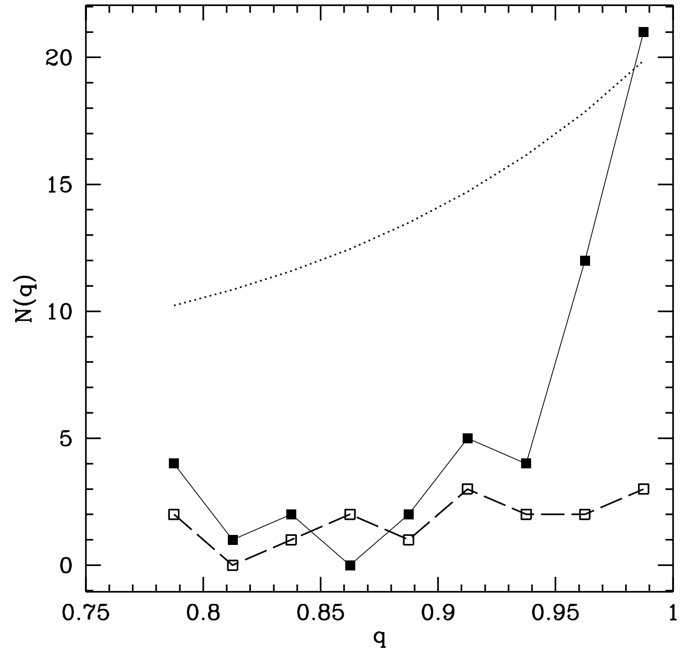

Fig. 2. The mass ratio distribution in the two period ranges: short, 2–30 days (full line and filled symbols, 52 systems) and long, 50–10000 days (dashed line and empty symbols, 15 systems). The number of objects in 0.025 bins in q is plotted on the vertical axis. Dotted line indicates possible sample bias as discussed in the text.

discusses the twin pair of O9 stars, Y Cyg. Similarly, this phenomenon is not restricted to short-period systems: visual binaries with equal-mass components are rather common. However, the universal significance of peak near $q = 1$ in mass ratio distribution is difficult to check. This is why we consider here only solar-type short-period systems where this peak *is* significant.

The 82 double-lined binaries of luminosity classes V and IV with primary components' spectral types from K0V to F5V were selected from the Eighth Catalogue of spectroscopic binary orbits (Batten et al. 1989, hereafter SB8). In the 10 years since catalogue compilation many more orbits have been published. Without attempting to be exhaustive, I collected from the literature new double-lined orbits for the same range of primary masses. Relevant parameters and references to this *extended* sample of 47 binary orbits (SB+) are given in Table 1. The advantage of using SB+ is that it is completely independent of SB8 sample, is based mostly on the correlation radial velocities, and contains good-quality orbits.

In Fig. 1 the mass ratio q is plotted against the logarithm of the orbital period for both SB8 and SB+ samples. When the $q = K_1/K_2$ is larger than 1, its reciprocal value is plotted. The existence of numerous SB2 with $q < 0.8$ proves that for $q > 0.8$ there remain practically no selection effects in q. Indeed, the lower mass ratio limits of single-lined binaries in SB8, also plotted in Fig. 1, are below $q = 0.8$, because at higher q the contrast of secondary lines relative to those of primary is more than 0.2, and secondary is always detected.

The systems with $P < 1^d$ are mostly contact; their secondary components are different from normal dwarf stars, their mass ratio is likely to have been modified by mass transfer and is of no relevance for binary formation mechanisms discussed here.

Both samples show similar behavior of $q(P)$:

- A strong concentration of systems in the interval $q = (0.95,\ 1)$ is found for periods between 2 and 30 days.
- On the contrary, few systems are found with $q > 0.95$ and periods from 50 to 1000 days. In this period range, the systems with smaller q do exist. They are more difficult to discover than $q = 1$ systems, so this is *not a selection effect*. At $P = 1000^d$ the radial velocity semi-amplitude is 15 km s^{-1}, well above the resolution limit of radial velocity spectrometers which are capable of resolving equal-component systems even at longer periods, as seen in Fig. 1.

The remarkable excess of short-period twin binaries is confirmed by the SB+ sample. An *absence* of such binaries at longer periods is a feature which was not clearly identified before. The existence of a sharp upper cutoff period around 40 days (or a component separation at periastron about 60 $R_\odot$) for twins provides a constraint for the possible theories of their formation.

In Fig. 2 we plot the distributions of mass ratio for the binaries in the selected period ranges, "short" (from 2 to 30 days) and "long" (from 50 to 10^4 days), in order to get quantitative idea about the excess of twin systems. Both samples, SB8 and SB+, were merged. There are only 15 long-period binaries, but the difference of the distributions is still highly significant. Long-period systems seem to have a smooth distribution of q. As for the short-period systems, they represent a mixture of two pop-

Table 1. Data on new spectroscopic orbits (SB+ sample)

HD/ Name	Sp./ B-V	$\log P$, days	q	Reference
G87-45	0.64	1.705	0.674	Latham et al. (1988)
G236-38	0.78	1.427	0.972	Latham et al. (1988)
16620	F8V	2.987	0.681	DM88
61994	dG5	2.743	0.716	DM88
105287	G5V	0.588	0.730	Imbert (1988)
213429	F8	2.801	0.549	D88
S999	0.77	1.003	0.877	Mathieu et al. (1990)
S1024	0.57	0.855	1.000	Mathieu et al. (1990)
S1045	0.55	0.883	0.995	Mathieu et al. (1990)
S1053	0.69	2.091	0.829	Mathieu et al. (1990)
+48 476	0.51	1.799	0.977	Latham et al. (1991)
17841	0.79	1.462	0.916	Latham et al. (1991)
20039	0.75	2.058	0.867	Latham et al. (1991)
G86-40	0.59	2.035	0.905	Latham et al. (1991)
+21 2442	0.80	1.492	0.972	Latham et al. (1991)
G66-59	0.64	1.031	0.914	Latham et al. (1991)
3443	G5V	3.960	0.791	DM91
13612	dF9	1.977	0.965	DM91
64096	G1V	3.933	0.955	DM91
137107	G2V	4.182	0.826	DM91
158614	G8IV	4.229	0.881	DM91
189340	G0V	3.253	0.764	DM91
191854	G5V	4.498	0.856	DM91
98439	F8V	2.997	0.980	Griffin (1991a)
6645B	F8V	0.664	0.913	Griffin (1991b)
22403	G2V	0.286	0.673	SF92
203454	F8V	0.511	0.564	SF92
222317	G5V	0.792	0.671	SF92
+25 2511	G8V	0.551	0.957	D93
+52 3247	G0V	3.914	0.948	Tokovinin (1993)
2879B	F7V	1.434	0.812	Griffin (1994)
KW367	0.68	0.486	0.781	M94
KW495	F8V	1.555	0.930	M94
184865	F7V	1.022	0.912	Tokovinin (1995)
184866	F7V	3.096	0.935	Tokovinin (1995)
163840	G2V	2.945	0.659	M95
483	G2V	1.371	0.987	Griffin (1996a)
43358A	F6V	0.338	0.986	Griffin (1996b)
2918	F8V	1.418	0.981	Griffin (1997)
32093	G5	2.270	0.715	Tokovinin (1997)
35317	F7V	1.354	0.747	Tokovinin (1997)
895C	G7V	0.780	0.954	Tokovinin (1998)
22091C	F7V	0.574	0.946	Tokovinin (1998)
2942B	K0V	0.874	0.965	Tokovinin (1999)
3266	G2V	1.556	0.796	Tokovinin (1999)
8624	G3V	1.173	0.996	Tokovinin (1999)
100831	G7V	3.228	0.708	Tokovinin (1999)

References: DM88 - Duquennoy & Mayor (1988); D88 - Duquennoy et al. (1988); DM91 - Duquennoy & Mayor (1991); SF92 - Stockton & Fekel (1992); D93 - Dadonas et al. (1993); M94 - Mermillod et al. (1994); M95 - McAlister et al. (1995);

ulations: normal binaries with almost uniformly distributed q, and twins. The first population continues towards smaller q, and constitutes the majority of binaries. The fraction of twins f_{twin}, defined as the number of binaries in the $(0.95, 1)$ bin divided by the number of binaries in the $(0.8, 1)$ interval, is $73 \pm 13\%$. The fraction of binaries in the $q = (0.8, 1)$ interval remains uncertain, our best estimate is that twins represent some 10–20% of the total number of short-period binaries. The modest frequency of twins explains why their existence cannot be detected in small samples.

Table 2. Distribution of mass ratio in 2 samples of dwarf spectroscopic binaries for periods from 2 to 30 days

q	SB8	SB+	SB8($m < 7$)
0.7-0.75	4	2	2
0.75-0.8	4	1	3
0.8-0.85	2	1	1
0.85-0.9	1	1	1
0.9-0.95	4	5	2
0.95-1.00	22	10	8
f_{twin}	0.76 ± 0.16	0.59 ± 0.19	0.67 ± 0.24

Double-lined binaries are brighter than single-lined ones, and their detection in magnitude-limited samples is thus privileged. The bias in favor of SB2 is proportional to the increased volume of space where they are found, that is to $(1 + q^{\gamma})^{3/2}$, where γ is the exponent relating mass to optical luminosity. Standard stellar data lead to $\gamma \approx 6$. Corresponding selection factor is plotted in Fig. 2 in arbitrary units (dotted line). It falls slowly with decreasing q and cannot account for the sharp peak. The actual selection effect is smaller because our sample is not exactly magnitude-limited (see the longer-period systems).

In Table 2 the data on the q distributions are given separately for the two independent samples considered here. To make sure that the excess of twins in SB8 is not due to the inclusion of the orbits of faint eclipsing binaries, the distribution for bright ($m < 7$) sub-sample of SB8 is also given.

The reality of $q = 1$ peak is still not generally accepted. Fekel et al. (1987) have not found it in a sample of 15 chromospherically active double-lined binaries: $f_{twin} = 0.33 \pm 0.17$, compared to $f_{twin} \approx 0.73$ found here. The $q = 1$ peak was not found by DM91 among nearby solar-type dwarfs, although a mass ratio distribution slightly rising towards $q = 1$ was obtained from their data by Mazeh et al. (1992). The DM91 sample includes 11 binaries with periods from 2 to 30 days, of which 3 are double-lined ($q > 0.8$), and two of them (HD 4676 and HD 146361) have $q > 0.95$, giving $f_{twin} = 0.67$. If the q distribution were uniform, only 0.55 binaries with $q > 0.95$ would be expected, with a Poisson probability of 0.11 to detect 2 and more such objects. Thus, twins seem to be present in the DM91 sample.

It might be asked if $q = 1$ peak is not produced by some subtle observational bias affecting radial velocity semi-amplitudes, which could be related to the use of photographic spectra with insufficient dispersion. The confirmation of the peak's reality by the SB+ sample and by the brighter objects in SB8 speak against these doubts. Still, in September 1998 I re-measured the semi-amplitudes for the two faint binaries from the SB8 catalogue

Table 3. Re-measurement of mass ratios for 2 binaries

Name	Number in SB8	$q_{\rm old}$	$N_{\rm obs}$	$q_{\rm new}$
MM Her	1017	0.98	6	0.93 ± 0.03
EZ Peg	1434	0.99	4	0.99 ± 0.02

with class c orbits. The observational technique used (correlation radial velocity spectrometer) is the same as in Tokovinin (1999), it gives unbiased velocity amplitudes. In fact, only amplitudes, center-of-mass velocities and initial epochs were fitted to our observations. The results are given in Table 3 which lists object names, their numbers in SB8, old mass ratio values, number of new observations, and the re-measured mass ratios. As expected, these observations prove that the worries about possible mass ratio bias in SB8 are not justified.

Among the SB8 main sequence binaries with primary less massive than 1.5 $M_\odot$ and periods between 2 and 30 days, 2 single-lined and 4 double-lined systems belong to Hyades. These SB2s have catalogue numbers 228, 236, 277, 278, and all but one have $q > 0.95$, indicating a high twin frequency in this *distance-limited* sample. Thus "spectroscopic" twins are related to cluster binary sequence. However, this relation is not simple, because binary sequence also contains wider twin pairs (Mermillod & Mayor 1999) and binaries with mass ratio less than 0.95 (Hurley & Tout 1998).

There are no systematic differences between twin and non-twin binaries in the period-eccentricity relation, as already noted in LR79. Many twins with $P > 5^d$ have eccentric orbits.

It was established before that the components of spectroscopic binaries are not complete "strangers" and show a tendency to have more similar masses than those of visual binaries (DM91, Mazeh et al. 1992). At $P < 40^d$ this parental tendency continues and there is a distinct population of pairs with almost identical components. Whatever is the mechanism which produced the majority of the short-period binaries, it is conceivable that twins originated in a different process, which was operational only for orbital periods shorter than 40^d (LR79). Let us examine possible mechanisms leading to the formation of twins.

3. Possible mechanisms of twin binary formation

3.1. Mass transfer

The theory of mass transfer was very successful in explaining the evolution of some binaries, e.g. Algol. It seems natural to suggest that at pre-main sequence (PMS) stages of stellar evolution mass transfer could have re-distributed the mass between binary components (Eggleton 1995).

Let us suppose that in a binary star with PMS components the separation at periastron a_{min} gradually decreases. This can be caused by the transfer of angular momentum to the circumbinary disk or jet. We know that all orbits are initially eccentric, hence the components begin to interact at periastron. The Roche lobe concept is not valid for eccentric orbits, but there is an equivalent of the instantaneous Lagrange point L_1, such that a test particle at L_1 is in unstable equilibrium between the components.

If the surface of primary is the first to touch L_1, mass can be transferred to the secondary, like in the classical Roche overflow case. This will lead to period shortening (which further enhances the mass transfer), but the orbit circularization due to mass transfer acts in the opposite way. Detailed calculations of Mathese & Whitmire (1984) show that eccentricity decreases faster than period, and the periastron separation may even increase after mass transfer. Neglecting this complication, we might suppose that a self-stimulating mass transfer leads to mass equalization and then stops because there will be no further orbit shortening. Components are left to contract on their own and will eventually form a twin detached binary.

This scenario is not likely to be realistic. It is the *secondary* that would be the first to reach L_1, and it would transfer mass to primary, decreasing q. Let us see why. If R_{L1} and R_{L2} are the distances from components' centers to L_1, and R_{*1} and R_{*2} are the stellar radii, we may write

$$\frac{R_{L2}}{R_{L1}} = q^\alpha \ \text{ and } \frac{R_{*2}}{R_{*1}} = q^\beta, \tag{1}$$

where β is the exponent in the mass-radius relation, $R \propto M^\beta$. Dividing these two relations, we compare the degree of contact for the two components:

$$\frac{R_{*2}}{R_{L2}} = \frac{R_{*1}}{R_{L1}} q^{\beta-\alpha}. \tag{2}$$

We know from the theory of Roche potential that $\alpha \approx 0.46$ for $q \approx 1$. Mass-radius relation for 10^6 yr old PMS stars yields $\beta \approx 0.3$ (cf. models of Forestini, 1994), for fully convective stars $\beta = 1/3$. The exponent $\beta - \alpha$ in Eq. 2 is negative, which means that the secondary is always closer to the contact than the primary. In a semi-detached binary with PMS components mass will be transfered from the secondary to the primary, and q will decrease. Such a transfer will probably be not self-stimulating because it increases the orbital period. Whelan (1970) already considered a PMS contact binary with equal components and found that it would be unstable with respect to mass transfer: the mass ratio would rapidly decrease from 1 to 0.39.

The situation is opposite when the components will have reached the Main Sequence (MS), and β is close to unity. Now $\beta - \alpha$ is positive. If the orbit shrinks, it is the primary that will be the first to reach contact and to share mass with its smaller brother. For this process to begin, the separation at periastron must be about 2 solar radii. We have seen that twin binaries are found for $a_{min} < 60 R_\odot$. It is hence difficult to explain the existence of twins by mass transfer at MS stage, unless a process of *widening* the orbit after mass transfer is found.

3.2. Fragmentation/fission

It has been suggested by Lucy & Ricco (1979) that twins result from a particular fragmentation mode at late stages of collapse. The size of a protostar at this stage must correspond to the orbit size of twins, i.e. about 60 $R_\odot$. However, the modern star formation theory does not predict such a fragmentation. The fragmentation during the H_2 dissociation suggested by Bonnell

& Bate (1994) was not confirmed in more recent simulations by Bate (1998). Thus, this mechanism seems unlikely.

3.3. Accretion

Formation of close binary stars would be impossible without orbital decay, because initial component radii were larger that their actual separation. Interaction with a circumbinary disk is the most likely candidate for orbital decay mechanism. Binary star clears a gap in the disk, although matter can still flow through the gap (Artymowicz & Lubow 1996). Angular momentum is transferred to the outer disk, increasing the eccentricity. At the same time dissipative interaction with accreted matter decreases period due to energy losses. The combined action of these two processes must lead to the formation of close binaries with eccentric orbits.

It is generally accepted that accretion of interstellar matter continues while low-mass PMS stars follow their evolution towards MS. Binary stars are already formed at this stage. The evolution of stellar masses and orbital parameters of PMS binaries proceeds thus simultaneously and is determined by the in-falling matter. Bate & Bonnell (1997) suggest that a tendency towards equal masses can be explained by a preferential growth of the secondary component because for close binaries the specific angular momentum of accreted matter is larger than that of binary. This model was further developed by Bate (2000), who have shown that, indeed, the mass ratio of close binaries can be strongly biased towards 1 by accretion.

For this process to be effective, a binary must accrete a significant portion of its mass, i.e. it must be already close while still surrounded by a massive envelope. Probably here lies the explanation of the difference between twins, which somehow had short periods at an early evolutionary stage, and "normal" short-period binaries which were braked by disks at later stages, when the remaining circumbinary matter was not sufficient to significantly alter the mass ratio, while still causing orbit decay. In this scenario, twins must have only short periods, as actually observed. Initial period shortening could be provided by dynamical interactions in multiple systems (see below).

Some low-mass PMS spectroscopic binaries indeed have equal masses (Mathieu 1994). Recently Mathieu et al. (1997) and Basri et al. (1997) have shown that accretion is continuing in the PMS twin binary DQ Tau with $P = 15.8^d$, $e = 0.58$ and $q = 1.00 \pm 0.03$. Other possibly PMS twins are V824 Ara ($q = 0.93$, Eggen 1995) and BY Dra ($q = 0.98 \pm 0.07$, Vogt & Fekel 1979). Accretion with orbit decay is thus a viable (and partially supported by observations) mechanism for explaining the formation of twins.

3.4. Multiple stars

It is an observational fact that many twins have distant tertiary components. Examples of twin binaries in multiple systems are HD 202908 (Fekel et al. 1997, periods 78^y and 4^d) and objects from Table 1: HD 895C ($370^y + 6^d$), HD 22091C ($600^y + 3.8^d$), HD 2942B ($18000^y + 7.5^d$), and HD 8624 ($100000^y + 15.9^d$). A faint physical companion to BY Dra at $16''$ was reported by Zuckerman et al. (1997). This companion was difficult to detect. It cannot be excluded (although difficult to prove) that *all* twins that are actually listed as binary are in fact members of multiple systems with yet undiscovered components.

The presence of a tertiary companion may give an important clue to understanding the origin of twins. As we have seen, to produce a mass ratio near 1 a strong accretion onto a close binary is needed. Dynamical interaction in a multiple system of protostars may lead to the formation of such close binaries at a sufficiently early stage. Additionally, tertiary components enhance the accretion of the circumbinary material onto the inner binary. For binaries in open clusters the role of tertiary could have been played by a close passage of another cluster member.

It is possible however that there is no direct relation between twins and multiples. Frequent occurrence of twins in multiple stellar systems can be understood if there is a common factor in their formation mechanisms. For example, the presence of significant circumstellar matter may have produced twins by accretion and orbit decay, and at the same time may have enhanced the capture of tertiary components by dissipating their gravitational energy, producing multiple systems.

The dynamics of triple stellar systems offers an additional mechanism to produce close binaries by the common action of Kozai cycles and tidal dissipation, as shown by Kiseleva et al. (1998). When initial orbits of the inner and outer binaries are approximately perpendicular to each other, the eccentricity of the inner orbit increases and may approach 1. Then the components may come into contact at periastron, making possible a mass transfer from primary to the secondary if the stars are already on the MS.

This scenario could explain why only a fraction of solar-type close binaries is converted into twins: orbits of inner and outer systems must be almost perpendicular in order to have high eccentricity modulation. However, it seems unlikely that after mass transfer the component separation can be again increased up to several $R_\odot$, because the inner orbit will be circularised and the Kozai mechanism will no longer be operational (Kiseleva et al. 1998). Moreover, the dissipative action of stellar tides probably tends to circularize the inner orbit well before the components can actually get into contact.

4. Conclusions

It is confirmed that solar-type dwarf binaries have a statistically significant excess of systems with mass ratio more than 0.95 (twins) at periods less than 40 days. In the period range from 2 to 30 days twins constitute from 10% to 20% of the total binary population. There is no $q = 1$ peak at longer periods.

From the discussion of the possible formation scenarios is is clear that twins cannot result from a mass transfer at protostellar stage and are not likely to be produced by fission. On the other hand, accretion onto a close binary explains the tendency of mass ratio towards 1. Twins can be understood as binaries that became relatively close (possibly through dynamical interaction in multiple systems) while still surrounded by massive envelopes. Many twins do have tertiary components. It would be interesting to look for such components around all twins.

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