# Multiple Stars: Physics vs. Dynamics

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**Summary.** We review physical and dynamical parameters of multiple stars. Possible scenaria of multiple star formation are discussed: their birth in dense cloud cores and the decay of small stellar groups and clusters. We compare physical and dynamical features of simulated multiple stars formed by these processes with the actual multiple stars. Multiplicity function, their period, eccentricity and mass ratio distributions, hierarchy of the structures are analysed. Also we discuss multiple systems where the apparent ages of the components are different. Such diferences can be explained by poor evolutionary tracks for low-mass stars, by formation of such systems by capture or by merging of components during dynamical evolution of multiple stars.

## 1 Introduction

Many stars were formed in clusters and small groups [1]. The actual multiple stars can contain an information concerning their formation processes. So the physical properties of components, dynamical stability or instability may reflect some details of their formation and evolution.

The dynamics of a system is related to its actual configuration. Historically, the configurations of multiple stars were separated into two types: trapezia (or non-hierarchical) systems and $\epsilon$ Lyrae (or hierarchical) systems. We suggest to introduce an intermediate type — low-hierarchy systems. As one example of such systems we consider the quadruple system HD 40887 (Fig. 1 and these Proceedings).

Note that an apparent configuration on the sky is not the same as the actual configuration in space. This is due to the projection effect. Even the type of a configuration may change.

Systems with strong hierarchy are stable with a high probability. The motions in such systems are almost Keplerian. Trapezium-type systems have a completely different behavior. As a rule, these systems are unstable. The motions of stars have a character of chaotic dance and the evolution is ended by a formation of a stable configuration, binary or hierarchical multiple. The actual trapezia-type stars must be dynamically young.

We consider three possible scenaria for multiple system formation:

– escape from unstable non-hierarchical small groups or clusters;

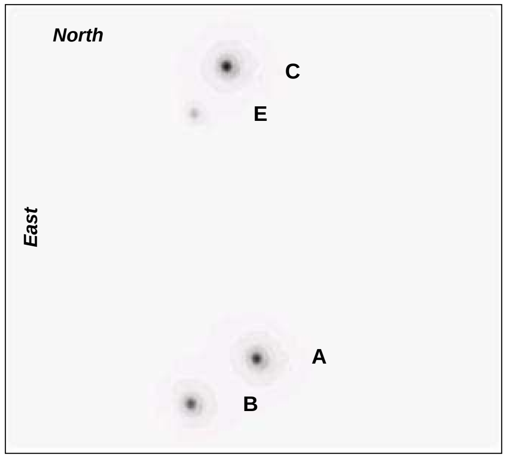


**Fig. 1.** Apparent configuration of a quadruple system HD 40887

- common formation as a stable or an unstable unit;
- capture in the galactic field or in the field of a common gas-star complex.

Below we consider the first scenario in more detail.

It is interesting to note that recently Goodwin and Kroupa [2] have shown that protostellar cores must typically produce only two or three stars.

## 2 Statistics of Binaries and Multiples

Let us consider some statistical properties of binary and multiple stars. These properties are used to compare the simulated and observed systems.

One of the important characteristics is the multiplicity function. This is the ratio $f_n$ of the number of the systems with the multiplicity $n$ to the same quantity for the multiplicity $n-1$. The results are given in the Table 1 [3].

**Table 1.** Multiplicity function from [3]

| $n$ | 3 | 4 | 5 | 6 | Average 4,5,6 |
|---|---|---|---|---|---|
| $f_n$ | 0.11 | 0.22 | 0.20 | 0.36 | 0.26 |
| | $\pm$ 3 | $\pm$ 2 | $\pm$ 4 | $\pm$ 14 | $\pm$ 5 |

This ratio $f_n$ is about 1/4. Only for $n = 3$ it is two times smaller. However, in the nearest solar neighborhood this ratio is $f_3 = 0.20$, i.e. also about 1/4. A very similar result $f_3 = 0.21$ was found for the final states of decay of small non-hierarchical stellar groups. This agreement confirms the hypothesis that many double and stable triple stars were formed initially inside small non-hierarchical stellar groups.

An important information could be deduced from the distributions of orbital elements and mass ratios. We consider such distributions for two samples of binary stars:

1. the binaries where the primary component has the spectral type similar to the solar one (late F or G) [4];
2. spectroscopic binaries where a primary is also of late spectral type (F7 to late K) [5].

Both samples were corrected by the authors for selection effects.

The distributions of the logarithm of the orbital period are shown in Figs. 2 and 3. The first sample shows a unimodal distribution similar to the Gaussian one. The second one shows a rather bimodal distribution. The reason for the difference between the distributions in Figs. 2 and 3 is unclear. The bimodality of the period distribution in Fig. 3 can be explained by two factors: 1) underestimation of selection effects for $P \approx 100^d$ binaries; 2) two different formation mechanisms for close and wide spectroscopic binaries.

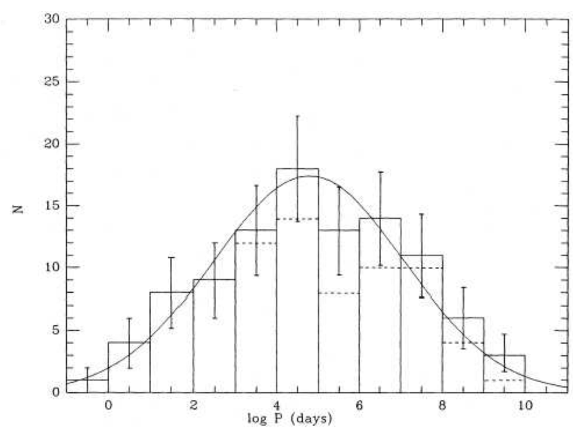


**Fig. 2.** Period logarithmic distributions according to [4]

The period-eccentricity diagrams for these samples are similar (Figs. 4, 5). There is a general growth of the median eccentricity with period. The circularization of short-period orbits is probably caused by tidal interactions of components.

The mass ratio distributions reflect the initial mass spectrum, but also evolutionary processes in the systems (both dynamical and astrophysical). This distribution seems to be a bimodal or even three-modal (Fig. 6). For the short period orbits, there is a marked population of twins where both components have similar masses. This multimodality could evidence an existence of at least two mechanisms of binary star formation.

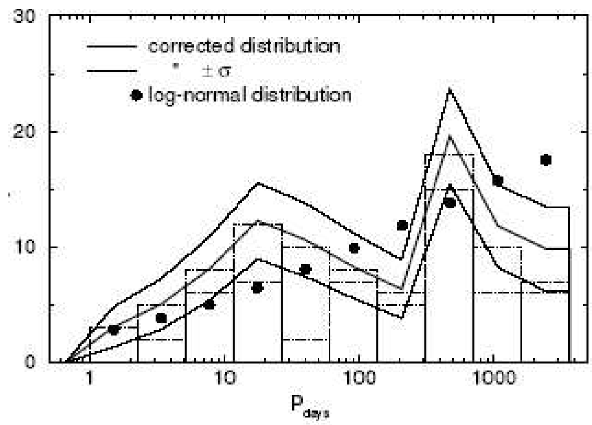


**Fig. 3.** Period logarithmic distributions according to [5]

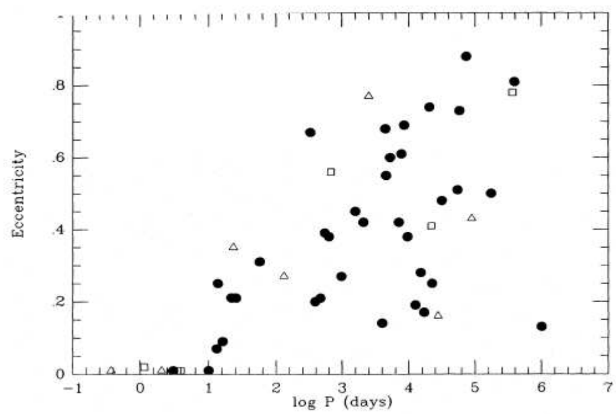


**Fig. 4.** Period–eccentricity diagram according to [4]

Let us compare observed binaries and multiples with stable final products of a simulated decay of small non-hierarchical groups (Fig. 7).

The eccentricities of escaping and final binaries are distributed according to the Ambartsumian-Heggie law $f(e) = 2e$. The same law is valid for wide binaries in the solar neighborhood according to [3].

The period-eccentricity diagrams of real and simulated binaries are slightly different (Figs. 4, 5, and 8). However, we note that the diagram for simulations is given here only for one value of initial group size $R = 100$ AU. Here close binaries where tidal effects may be essential are absent. At the same time, for long period binaries the period-eccentricity correlation cannot be clearly seen in Fig. 4, 5, and 8.

The mass ratio distributions are also similar (Figs. 6 and 9). The phenomenon of "twins" is clearly seen for escaping binaries, whereas the distri-

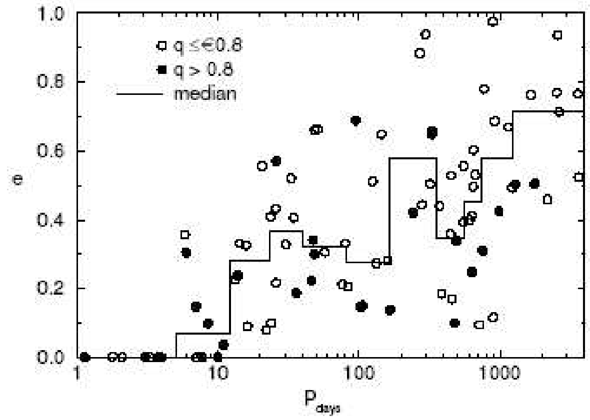


**Fig. 5.** Period–eccentricity diagram according to [5]

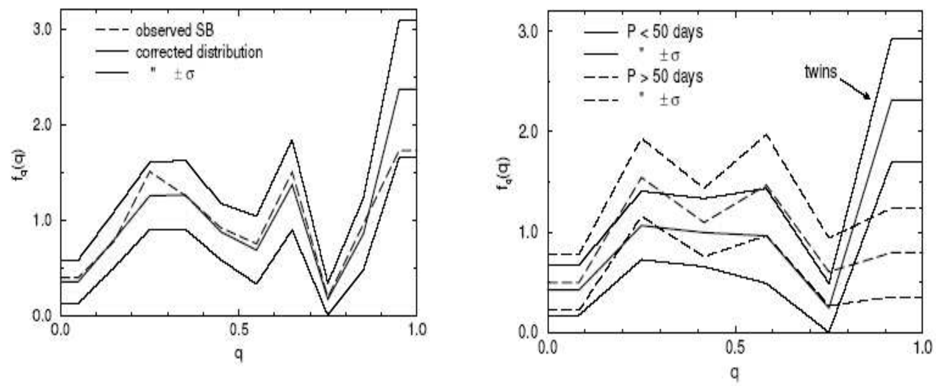


**Fig. 6.** Mass ratio distribution according to [5]

bution for the final binaries is approximately flat at $q > 0.2$. The qualitative agreement is observed, although quantitative differences are also evident.

Now we compare observations and simulations of triple stars.

Table 2 contains the mean and median values for the ratio of periods and eccentricities of inner and outer binaries in stable triples — both the final products of simulated small-group dynamical decay and the observed triple stars.

The histograms in Figs. 10 and 11 show the distributions of the period ratio.

The hierarchy degree is high in both samples. The distributions of the period ratio are qualitatively similar — both are unimodal. However, the asymmetries have different signs.

The mean and median eccentricities of inner and outer binaries in the observed triplets are slightly less than in the simulated triples. In inner bi-

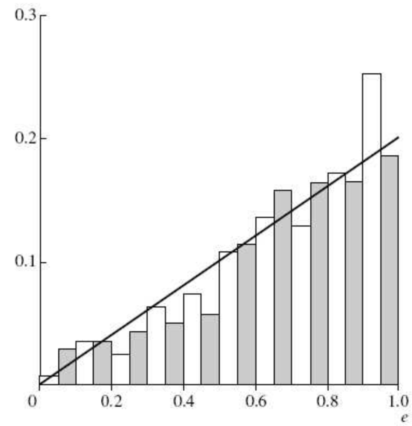


**Fig. 7.** Eccentricity distributions for final (white columns) and escaping (gray columns) binaries according to [6]. The solid straight line corresponds to the $f(e) = 2e$ law

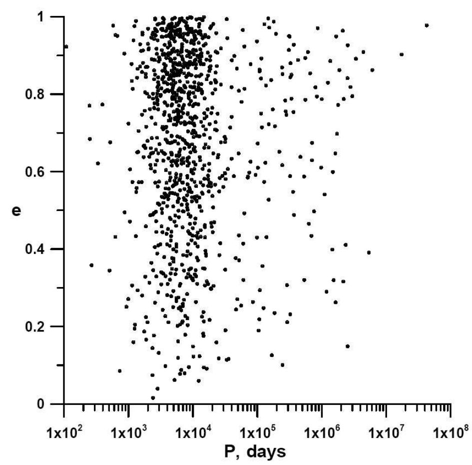


**Fig. 8.** Period–eccentricity diagram according to numerical simulations [6]

**Table 2.** Mean and median parameters of stable final triples according to simulations [6] and observations [7]

| | $\overline{\frac{P_{in}}{P_{ex}}}$ | $(\frac{P_{in}}{P_{ex}})_{\frac{1}{2}}$ | $\overline{e}_{in}$ | $(e_{in})_{\frac{1}{2}}$ | $\overline{e}_{ex}$ | $(e_{ex})_{\frac{1}{2}}$ | $n$ |
|---|---|---|---|---|---|---|---|
| observations<br>$P_{in} > 10^d$ | 0.040<br>±0.010 | 0.013 | 0.37<br>±0.04 | 0.39 | 0.38<br>±0.04 | 0.40 | 38 |
| simulations | 0.013<br>±0.001 | 0.011 | 0.61<br>±0.03 | 0.64 | 0.51<br>±0.02 | 0.51 | 80 |

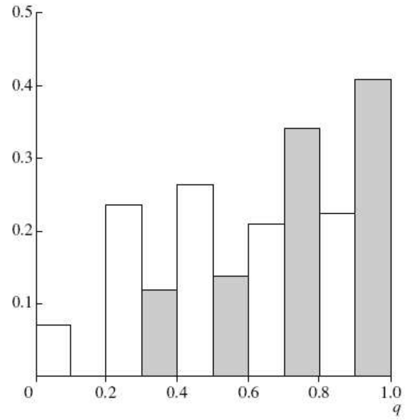


**Fig. 9.** Mass ratio distribution for final (white columns) and escaping (gray columns) binaries according to [6]

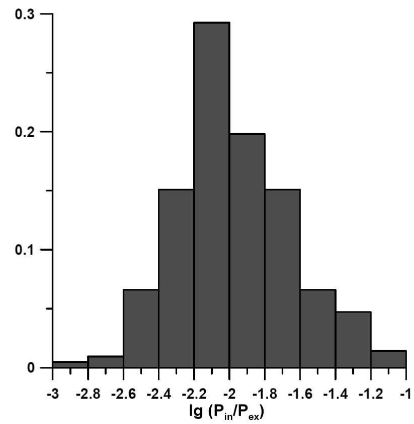


**Fig. 10.** Period ratio distribution for final stable triples according to [6]

naries, the partial circularization could be caused by the tidal interaction of components. Also we have to bear in mind a bias effect: it is difficult to compute orbits of very eccentric binaries.

Another interesting parameter of hierarchical triples is the angle between the orbital angular momenta of inner and outer binaries. It characterizes the mutual inclination between their orbital planes. Figure 12 shows the cumulative distributions of this angle for simulated triplets and triple stars from the Multiple Star Catalogue, according to Sterzik and Tokovinin [8].

There is a slight difference between observations and simulations for the angles greater than 90° (retrograde motions). This difference may be indicative of some resonance effects, like the Kozai-Lidov effect.

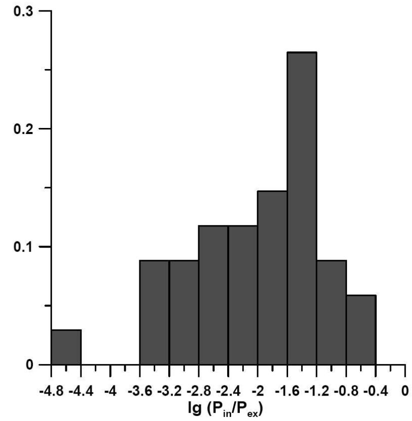


**Fig. 11.** Period ratio distribution for observed triples according to [7]

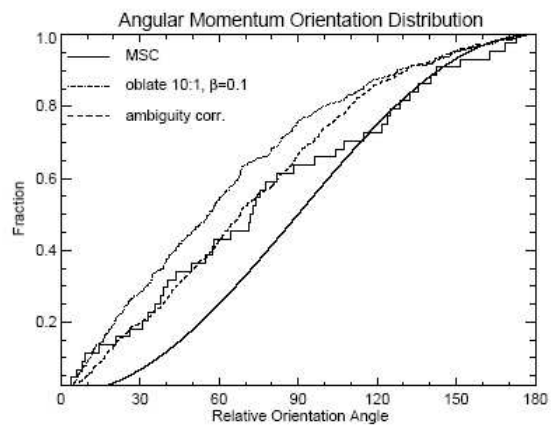


**Fig. 12.** Cumulative distributions of the angle between the orbital angular momenta of inner and outer binaries for stable triples simulated in small group decay and the observed triples according to [8]

Thus, we have the qualitative agreement between the data for observed and simulated binaries and triples. This agreement can be considered as an additional argument in favour of the hypothesis that the majority of these systems might be formed by the decay process of small non-hierarchical stellar groups.

## 3 Stability of Low-hierarchy Multiples

A more interesting question is the dynamical stability of observed multiple stars. In order to study this problem, we have compiled a sample consisting of sixteen triple stars and two quadruple stars (for details see [9] and [10]). The close binaries were considered as a single component.

Two methods of stability study were used: 1) several well-known stability criteria for triple systems and 2) numerical simulations of past and future evolution for all systems during one million years (sometimes ten million years).

The input data on orbital elements and masses have some uncertainties. In order to check the effect of these errors, we have made the Monte Carlo simulations — orbital elements and masses were varied using independent Gaussian distributions, where the mean values were taken as the observed values and the dispersions are the same as root mean square errors. One thousand runs were considered for each system.

Two populations of multiple stars were found: probably stable and probably unstable. The gap between these two populations is rather wide. For "stable" systems, we estimate the decay probability $P_d < 0.1$. A non-zero value of $P_d$ could be explained by too big orbital parameter errors taken into consideration. At the same time, for "unstable" systems we found $P_d > 0.9$ during time interval 1 Myr (more than $10^3 \cdot P_{ex}$). We may suppose that the remaining systems will decay at a longer time. Here we give the list of probably unstable systems: HD 40887 (Gliese 225.2) — quadruple, HD 76644 ($\iota$ Uma = ADS 7114) — quadruple, HD 136176 (ADS 9578) — triple, HD 150680 (ADS 10157) — astrometric triple, HD 222326 (ADS 16904) — triple. Among them there are two quadruplets and three triplets.

Possible explanations of apparently unstable systems are:

1. Errors of observations and interpretation.
2. Physical youth of components.
3. Some additional effects are responsible for the physical stability of the system (mass loss etc.).
4. Some additional effects led to the formation of the unstable system (merging etc.).
5. Temporary capture via encounter of a binary (multiple) system and a single (multiple) star.
6. Stability loss via an encounter of a stable multiple star with a massive object (molecular cloud, black hole etc.).
7. Product of dissipation of a stellar group or a cluster.

We believe that the first point is not the only possibility. We have roughly estimated the expected number of unstable systems within 200 pc from the Sun due to the last three mechanisms. The expected number of unstable systems within this sphere for the scenarios 5-7 is about $1 \div 10$ ($P_{ex} < 10^3$ yr). This is not negligible.

As for our probably unstable systems, we can say that each object from the list has the problems concerning its multiplicity or/and orbital parameters. So, our conclusions about their instability are preliminary, and additional studies are extremely welcome.

## 4 Discussion and Conclusions

Multiple stars could be considered as an astrophysical laboratory. Mostly, the components of the same multiple system have the same age. Therefore we can compare the evolutionary status of the stars of the same age, but with different masses.

One possible scenario of the origin of single, binary, and stable multiple stars due to a decay of small non-hierarchical groups was suggested by Larson [1]. Our statistical comparative analysis of simulated and observed systems has confirmed this point of view.

One new interesting result has been found by Goodwin and Kroupa [2]. They show that most stars were produced in binary or triple systems.

However, sometimes the components of multiple stars could have different ages, as derived from the evolutionary tracks. Four examples of such systems were found by Popper [11]. Here the low-mass components have larger ages. The most plausible explanation of this fact is the unreliability of the used evolutionary stellar models for low-mass stars. However, we cannot reject a hypothesis that some of these systems were formed by capture, and the age differences are real.

Our conclusions are:

1. One can separate multiple stars into high-hierarchical, low-hierarchical, and non-hierarchical.
2. High-hierarchical systems are long-term stable.
3. Non-hierarchical systems usually disrupt.
4. Low-hierarchy systems may be either stable or unstable.
5. A few scenarios of their instability are suggested.

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