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Mass ratios in multiple star systems

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Abstract. Recently a catalogue of 612 physical multiple stars was published by Tokovinin. The systems are generally hierarchical, i.e. they consist of binaries of different hierarchy levels. We have studied the mass ratios of the hierarchical binaries as a diagnostic of the origin of the multiple systems. The three-body statistical break-up theory is used to obtain likely mass ratio distributions in dynamically strongly interacting systems. A comparison with the catalogue data shows good agreement between theory and observations. This tells us that the multiple stars of the catalogue are not primordial but their properties are results of dynamical interactions where the three-body ejection process plays a key role.

Key words: binaries: general – celestial mechanics, stellar mechanics

1. Introduction

Multiple star systems could in principle result from many different routes of evolution:

1. They could be primordial, i.e. stars could have been born in more or less the same configurations as we see them today;
2. The stars could have "found" each other by chance since their birth and formed various hierarchical groupings; or
3. The primordial systems could have been under vigorous dynamical interaction, strong enough that the information on the initial groupings would have been completely lost.

With regard to the third option, there exists a statistical theory of three-body interactions (Monaghan 1976) which has been succesfull in explaining the outcomes of three-body experiments as well as observed properties of binary stars (Valtonen 1997a,b). Even though the theory was originally conceived as an explanation of the break-up of a bound three-body system, it actually also applies to the three-body scattering by hard binaries (Mikkola 1986). Thus it is natural to look at the predictions of this theory in order to test the third option.

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2. The multiple star data

The multiple star catalogue (MSC) of Tokovinin (1997) contains data on 612 physical multiple stars of multiplicity 3-7. The MSC is ordered by the levels of hierarchy: at the lowest level are the binaries, above them binaries where one component is itself a binary, and so on. In the catalogue a component which itself is a binary, is coded by letter **s**. Therefore we divide the catalogue in two: systems where at least one component is labelled **s**, and systems where neither component has this label. In our final listing we ignore the cases with uncertain mass data (labels **:**, **m**). Otherwise the whole catalogue is used.

We thus obtain two catalogues:

1. true binary catalogue (no **s**) and
2. hierarchical binary catalogue (with **s**).

The two catalogues have 437 and 662 systems or subsystems, respectively. Note that the same physical system enters many times into the catalogues since each contains several subsystems. Each subsystem is listed separately following Tokovinin (1997). As one would expect, the **s**-type systems are wider, and the periods longer, than the no **s**-systems (Fig. 1).

We then look at the mass ratio Q: the mass of the secondary divided by the mass of the primary. The component mass is the sum of the masses of the two stars in the **s**-systems. As the mass ratio distribution is expected to be a function of the mass (or spectral type) of the primary, we plot the distributions separately for G-type primaries, A-type primaries and B-type primaries. As a simplification, we have put the border line between G-type and A-type stars at 1.25 solar mass which in fact is the main sequence stellar mass in the middle of the F-type range. The border between A-type and B-type stars is put at 3 solar mass, the border between B-type and O-type at 16 solar mass, and the lower limit of G-type stars at 0.75 solar mass.

Fig. 2 shows an example of the mass ratio distribution for the true binary sample. It is for A-type primaries but it is quite representative of other spectral types as well. The most prominent feature is the concentration of the distribution toward equal masses, $Q \simeq 1$. This is almost certainly an observational selection effect (e.g. Trimble 1990) since it is quite different from the usual binary samples (e.g. Duquennoy & Mayor 1991). It is understandable that it is difficult to observe the two stars in

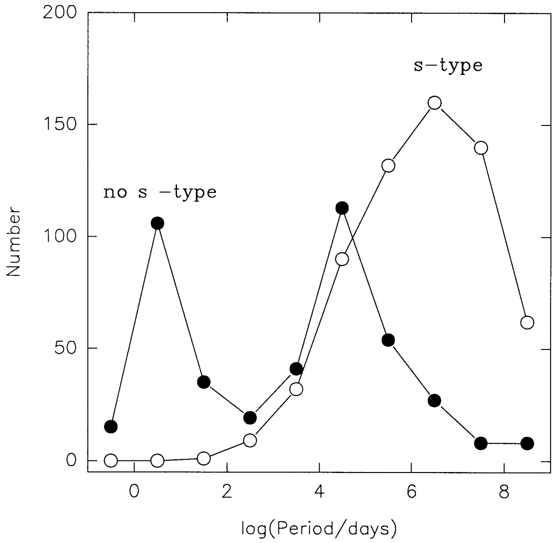

Fig. 1. The period distribution of the **s** (open circles) and no **s**-systems (filled circles) in MSC.

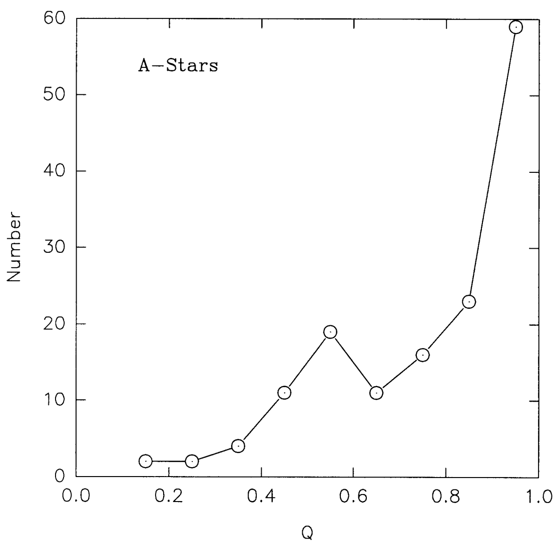

Fig. 2. The distribution of the mass ratio Q in the true binary sample of MSC. The mass of the primary star is in the interval of $1.25M_{\odot} \leq M \leq 3M_{\odot}$

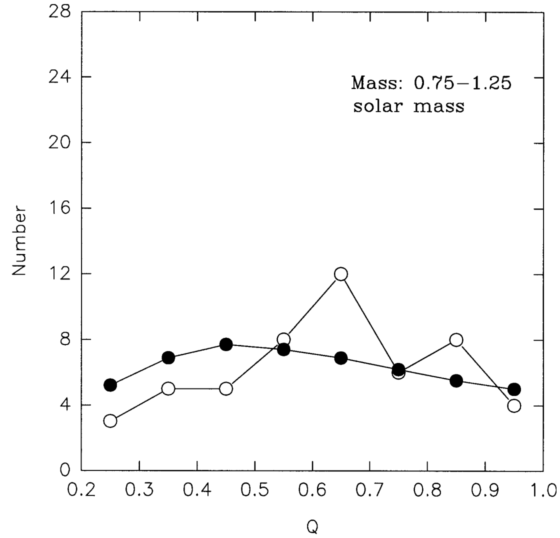

Fig. 3. The distribution of the mass ratio Q in the hierarchical binary sample of MSC (open circles) and the theoretical distribution after the ejection of two stars (filled circles). The mass of the primary star is in the interval of $0.75M_{\odot} \leq M \leq 1.25M_{\odot}$.

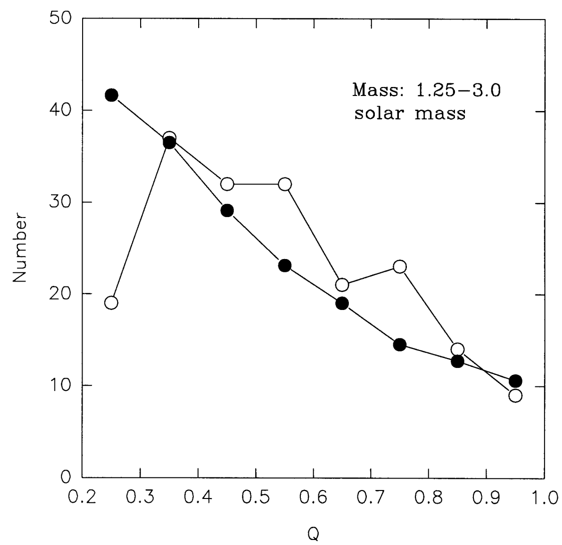

Fig. 4. The same as Fig. 3 except that the mass of the primary star is in the interval of $1.25M_{\odot} \leq M \leq 3M_{\odot}$.

the innermost tight binary if the masses are rather unequal (e.g. Zinnecker 1984).

The picture is quite different for the **s**-systems. Then the binary is wide and it is more easy to observe the two components even if they are not equal. Fig. 3 shows the observations (open circles) for the ‘G-type’ primaries (i.e. mass range 0.75–1.25 solar mass). The distribution of Q is fairly uniform. The following figures (Fig. 4–Fig. 6) give the same data for the heavier primaries. The distributions are peaked at low Q, and the dominance of the low Q increases with the increasing binary mass.

3. Three-body theory

The outcome of the break-up of a three-body system is well described by the statistical theory of Monaghan (1976). As far as the mass ratios are concerned, the theory gives the probability that mass m_s escapes from a system where the other two masses are m_a and m_b:

$$f(m_s) = \frac{m_s^{-2.5}}{m_a^{-2.5} + m_b^{-2.5} + m_s^{-2.5}} \tag{1}$$

(Mikkola & Valtonen 1986). To make use of this result, we generate randomly mass values m_a, m_b and m_s, calculate the probability from Eq. (1) that m_s escapes, which is also the prob-

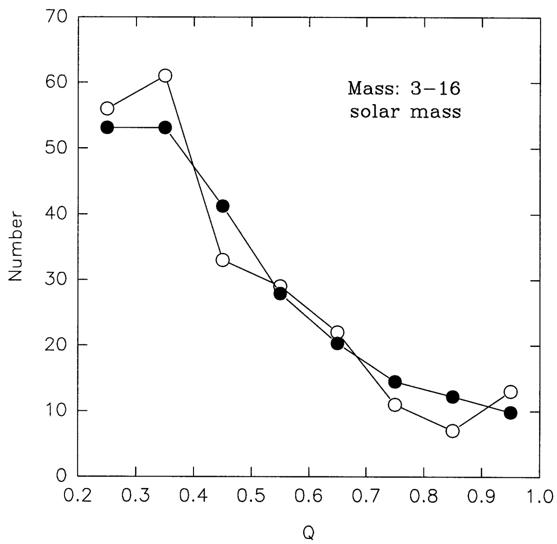

Fig. 5. The same as Fig. 3 except that the mass of the primary star is in the interval of $3M_\odot \leq M \leq 16M_\odot$.

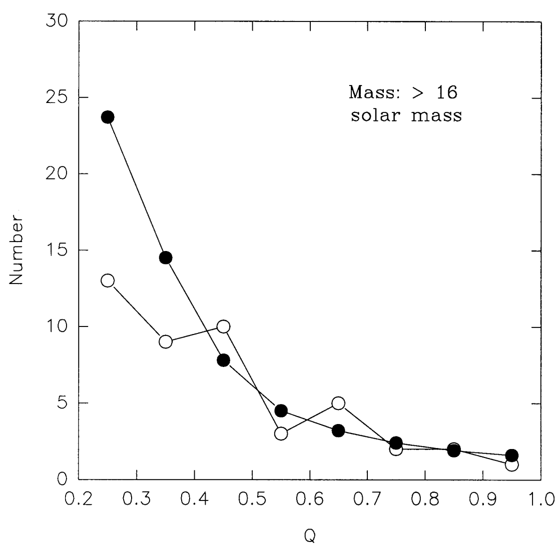

Fig. 6. The same as Fig. 3 except that the mass of the primary star is $M > 16M_\odot$.

ability that a binary of masses m_a and m_b is created. Thus also the distribution for the mass ratio m_a/m_b is generated.

The mass values m_a, m_b and m_s are picked randomly from the stellar mass function $\psi(m)$. We use a four-part function (m in units of $M_\odot$):

$$\psi(m) = 0.0848 \quad (0.058 \leq m \leq 0.4)$$
$$\psi(m) = 0.14(0.7 - m) + 0.0428 \quad (0.4 \leq m \leq 0.7) \tag{2}$$
$$\psi(m) = 0.01(m/1.3)^{-2.35} \quad (0.7 \leq m \leq 3)$$

and

$$\psi(m) = 0.0014(m/3)^{-3.2}(m \geq 3)$$

(Kroupa et al. 1990).

We have carried out Monte Carlo simulations in two different scenarios:

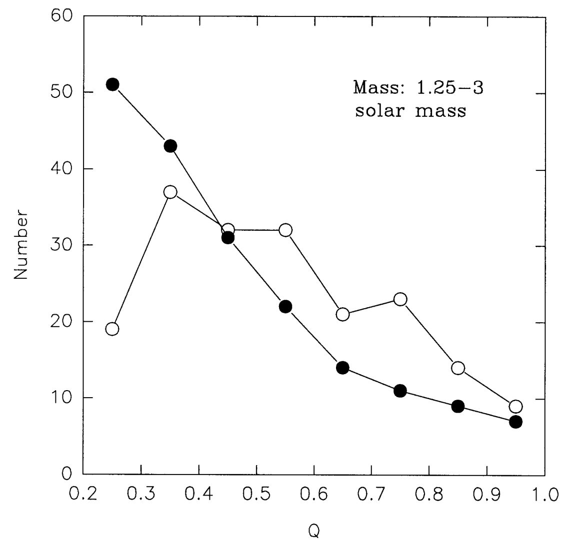

Fig. 7. The same as Fig. 4 except that the theoretical distribution is based on the ejection of a single star.

1. A single star is ejected from a triple system and a binary remains, i.e. Eq. (1) is applied once. The mass ratios in this case have been calculated previously and we refer the reader to Valtonen (1997a,b) for an illustration of the resulting distributions. We show an example of the theoretical distributions in Fig. 7 (solid dots).
2. The binary formed in the above process is itself a member of a higher level hierarchical triple system. A single star is ejected, and a hierarchical binary forms. Thus Eq. (1) is applied twice in succession. The solid points in Figs. 3–6 show the result of the calculation. The mass of the primary (either a single star or a binary) is indicated in the figures.

We note that the mass ratio distribution of process (2) behaves as a function of the primary mass very much like the observations of the MSC sample. The distribution is rather flat for low mass primaries but it steepens for high mass primaries. This steepening is due to the steepening of the mass function $\psi(m)$ for high m. However, the mass ratio distribution is considerably flatter than what one would obtain simply by random pairing from the initial mass function $\psi(m)$. The mass ratio distribution of process (2) is also a little bit flatter than the distribution arising from process (1). Fig. 7 illustrates the distribution from process (1), solid dots, in contrast to the obervations of the MSC hierarchical sample (open circles). Note that the observed distribution for true binaries in MSC (Fig. 2) is quite different from the theoretical result (Fig. 7, solid dots).

Besides the general rising or falling trends, the observed distributions (open circles) in Figs. 2–7 are consistent with random $\sqrt{N}$ fluctuations. The theoretical distributions have been scaled down from much larger samples and are thus smooth.

4. Discussion

It is not unexpected that the dynamical three-body theory should explain the hierarchical multiple star systems. They are typically wide (median orbital period 5000 yr) and thus subject to numerous stellar encounters. Just as in case of wide binaries, the mass ratios in hierarchical binaries seem to result from strong dynamical encounters. The original mass ratios are lost, whether they result directly from the formation process or from chance pairings of newly formed single stars.

The case of the true binaries in the MSC catalogue is less clear. There is a big contrast between the theoretical expectation and the observational sample. It may be that the close binaries are not subject to dynamical evolution to such an extent as the wide hierarchical binaries. On the other hand, the selection effects may favour observing equal mass binaries very strongly (Tout 1991). We suspect that the latter is probably true since the $Q \simeq 1$ peak shows up also in the long period true binary sample (~ 50% of the total sample) where the orbital period is greater than 30 yr. Previous work has established that wide binaries in the period range 1–10 yr (Evans 1995) do follow the distribution expected from the three-body theory (Valtonen 1997b). But it is also possible that the dissolution of the surrounding cluster, and the numerous dynamical interactions during this process, lead to a higher survival rate of the $Q \simeq 1$ binaries (Kroupa 1995).

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