ON UTMOST MULTIPLICITY OF HIERARCHICAL STELLAR SYSTEMS

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Abstract. According to theoretical considerations, multiplicity of hierarchical stellar systems can reach, depending on masses and orbital parameters, several hundred, while observational data confirm existence of at most septuple (seven-component) systems. In this study, we cross-match very high multiplicity (six and more components) stellar systems in modern catalogues of visual and multiple stars, to find candidates to hierarchical systems among them. After cross-matching with catalogues of closer binaries (eclipsing, spectroscopic, etc.), some of their components were found to be binary/multiple themselves, which increases the system’s degree of multiplicity. Optical pairs, known from literature or filtered by the authors, are flagged and excluded from the statistics. We have compiled a list of potentially very high multiplicity hierarchical systems that contains 10 objects. Their multiplicity does not exceed 12, and we discuss a number of ways to explain the lack of extremely high multiplicity systems.

Key words: Stars: binaries: general — binaries: visual

1. INTRODUCTION

Data on stellar multiplicity is important as a constraint on the problem of the
Table 1. Principal catalogues of visual double and multiple systems

| Catalogue, abbreviation, reference | C, P, S | M |
|-----------------------------------|---------|---|
| The Washington Double Star Catalog (WDS, Mason et al. 2016) | 242980 | 2-32 |
| Catalogue of Components of Double and Multiple Stars (CCDM, Dommanget & Nys 2002) | 105857 | 1-18 |
| Tycho Double Star Catalogue (TDSC, Fabricius et al. 2002) | 103239 | 1-11 |

C, P, S are numbers of catalogued components, pairs, and systems, respectively, M is multiplicity of catalogued systems.

formation and evolution of the Galactic stellar population. On the other hand, statistics of stellar multiplicity, i.e. the number of components, is poorly known, especially for multiplicities higher than three or four, and many questions still remain unresolved (see, e.g., the recent review by Duchêne & Kraus 2013).

The maximum number of components in a hierarchical multiple system depends on the number of hierarchy levels and can be estimated from theoretical considerations. A system is dynamically stable if, in a case of circular orbits, the outer orbital period exceeds the inner orbital period by a factor of five. For eccentric orbits, this factor is larger, increasing as $\propto (1-e)^3$ (Tokovinin 2004). The mean outer/inner ratio for the semi-major axis and period is 20 and 70, respectively. On the other hand, the number of levels in hierarchical stellar systems is limited by the tidal action of regular gravitational field of the Galaxy, gravitational perturbations from passing stars, and stochastic encounters with giant molecular clouds (see, e.g., Jiang & Tremaine 2010). Surdin (2001) demonstrated that, in these circumstances, the number of levels can reach values of 8 or 9, depending on masses and orbital parameters of the components. In the case of maximum dense “packing” of components in the system, hierarchical systems with 256 to 512 components can be produced.

On the other hand, there is no evidence to prove the existence of any hierarchical system having multiplicity of seven or higher. The most comprehensive catalogue of multiple systems (Tokovinin 1997) contains about 1350 hierarchical systems of multiplicity three to seven, and among the two catalogue septuple systems (AR Cas and $\nu$ Sco), at least the former one is a young cluster, i.e. is not necessarily hierarchical. This statistics is in a sharp contrast with the theoretical estimates given above. To eliminate this inconsistency, it is necessary to use additional sources of information, namely modern catalogues of double stars.

2. CATALOGUES OF DOUBLE AND MULTIPLE SYSTEMS

Principal modern catalogues of visual double stars contain systems of much higher multiplicity than seven (see Table 1). Actually, WDS contains several systems of even higher multiplicity than indicated in Table 1. They represent either results of searches for sub-stellar companions to nearby stars by high-contrast and high-angular-resolution imaging, where at least some of the objects are background stars (WDS 17505−0603, 65 objects; WDS 19062−0453 = $\lambda$ Aql, 107 objects) or results of speckle interferometric observations of stars in nebulae.
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Figure 1: Observational distribution of stellar systems on multiplicity $M$. Histograms represent distributions from principal catalogues of double and multiple stars: WDS (solid), CCDM (dotted), TDSC (dashed). Curves represent published statistics on hierarchical stellar systems; dotted curve: Orlov & Titov (1994) and Tokovinin (2001); solid curve: Tokovinin (2014). The curves are normalized on the number of binaries in WDS.

(WDS 05387−6906 = 30 Dor = Tarantula Nebula, 68 objects; WDS 05353−6523 = $\theta_1$ Ori = Trapezium cluster in Orion nebula, 39 objects) or miniclusters / common proper motion groups (WDS 19147+1918, WDS 20315+3347, WDS 13447−6348, WDS 18354−3122, WDS 23061+6356, 38 to 44 objects per system).

Note also in brackets that CCDM and TDSC contain some systems of multiplicity one. In the former case, this concerns astrometric binaries (with an invisible secondary component detected by its gravitational influence), while TDSC contains a fair amount of stars that the Tycho mission failed to resolve into components.

It is instructive to plot the distribution of catalogued stellar systems on their multiplicity and compare it to the observational data. Tokovinin (2001) presented statistics of catalogued multiple systems in the form $N_i/N_{i-1} = 0.11, 0.22, 0.20, 0.36$ for $i = 3, 4, 5, 6$, respectively, where $N_i$ is the number of systems of the $i$th multiplicity. These results are in a good accordance with conclusions made by Orlov & Titov (1994) in their study of multiple objects in the immediate ($d \leq 25$ pc) solar vicinity. Later Tokovinin (2014) studied hierarchical systems among F and G dwarfs in the Solar neighborhood and found the fraction of multiple systems with $1, 2, 3, \ldots$ components to be $54:33:8:4:1$. These results are plotted in Fig. 1. It can be seen that the most complete catalogue, WDS, satisfactorily images the Orlov & Titov (1994) and Tokovinin (2001) distributions, while the newer and deeper study by Tokovinin (2014) demonstrates a surplus of triple and higher-multiplicity systems in comparison with the catalogued systems (or, conversely, WDS contains superfluous, obviously optical, double stars).
The listed catalogues of visual binaries contain various data for evidently overlapping sets of objects, and no one of them contains all known visual systems. Thus, to use the complete dataset, it was necessary to cross-match these catalogues, i.e., to gather all available information on visual binary stars in a single list. A comprehensive set of visual binaries using data from the current versions of the three listed catalogues was compiled by Isaeva et al. (2015). However, as further analysis has shown, the applied cross-matching procedure worked quite well for systems of multiplicity about five or six, but often failed to correctly cross-identify components in systems of higher multiplicity, due to high spatial density of objects.

3. VERY HIGH MULTIPLICITY SYSTEMS: PROCEDURE, RESULTS,
   AND DISCUSSION

To compile a list of candidates to hierarchical stellar systems of maximum multiplicity (and estimate the value of this maximum multiplicity), as well as to finally solve the problem of cross-identification of multiple systems, we have performed a semi-manual identification of systems of multiplicity six and more in principal catalogues of visual double and multiple systems (see Table 1). The total number of such systems is 551. 175 of them are included in WDS only. The remaining 395 systems are included in more than one catalogue and, consequently, their components need cross-matching (the systems themselves were cross-matched by Isaeva et al. 2015 and analyzed in Kovaleva et al. 2015a).

Compiling the list of very high multiplicity systems, we were flagging optical pairs. The information about non-physical nature of a pair can be found in WDS and the textual Notes to WDS. We have also applied the criterion to select optical pairs suggested by Poveda et al. (1982), which revealed additional optical objects. The result can be seen in Fig. 2 (gray bars).

Photometrically unresolved binarity of some components can increase actual multiplicity of a system. In order to take this into account, we have cross-matched our systems with lists of closer binaries (orbital, interferometric, spectroscopic, eclipsing, X-ray systems, radio pulsars) using the Binary star database, BDB (Kaygorodov et al. 2012, Kovaleva et al. 2015b). Besides, indication of hidden binarity can sometimes be found in WDS Notes (34 cases). Information on sub-components of our very high multiplicity systems was found in catalogues of orbital (77 pairs), interferometric (425 pairs), spectroscopic (52), and eclipsing (16) binaries. The resulting distribution can be seen in Fig. 2 (the black contour).

Finally, we have excluded from our statistics those pairs that have no clear indication on their physical binarity, according to WDS and the textual Notes to WDS. As a result, we have compiled a list of 10 so-called “confirmed” systems of multiplicity six and higher. The list contains all systems included in the WDS, CCDM, and TDSC catalogues, and thus it is the most comprehensive list of stellar systems of multiplicity six and more. We provide extensive cross-identifications for components, pairs, and systems included in the list. We add data on photometrically unresolved binaries, taken from catalogues of closer pairs (spectroscopic, eclipsing, etc.) and flag optical pairs.

The final statistics is presented in Table 2. Column N1 contains the number of candidates to systems of multiplicity M (gray contour in Fig. 2). Column N2 contains the number of candidates to systems of multiplicity M, without optical pairs (black contour in Fig. 2). Column N3 contains the number of confirmed
Figure 2: Observational distribution of stellar systems on multiplicity $M$. The gray contour represents all systems. Gray bars represent all systems except optical pairs. The black contour represents all systems except optical pairs, but with the addition of closer, photometrically unresolved components (see text for details). Systems of multiplicity higher than 32 are discussed in the beginning of Section 2 and are not shown here.

Table 2. Multiple system statistics

| $M$ | $N_1$ | $N_2$ | $N_3$ | $M$ | $N_1$ | $N_2$ | $N_3$ | $M$ | $N_1$ | $N_2$ | $N_3$ |
|-----|-------|-------|-------|-----|-------|-------|-------|-----|-------|-------|-------|
| 6   | 138   | 54    | 5     | 6   | 15    | 14    | 1     | 21  | 4     | 1     | -     |
| 7   | 107   | 34    | 3     | 15  | 16    | 4     | 3     | 25  | 2     | 1     | -     |
| 8   | 76    | 20    | 1     | 17  | 5     | 2     | 25    | 1   | 1     | -     | -     |
| 9   | 42    | 16    | 1     | 18  | 6     | 2     | 27    | 1   | 1     | -     | -     |
| 10  | 39    | 13    | 1     | 19  | 4     | -     | 28    | 1   | 1     | -     | -     |
| 11  | 32    | 9     | 1     | 20  | 3     | -     | 29    | 1   | 1     | -     | -     |
| 12  | 23    | 3     | 1     | 21  | 2     | 1     | 30    | 1   | 1     | -     | -     |
| 13  | 14    | 4     | -     | 22  | 3     | -     | 31    | 2   | 1     | -     | -     |
| 14  | 13    | 1     | -     | 23  | -     | -     | 32    | 1   | -     | -     | -     |

$M$: multiplicity of systems; $N_1$: number of candidate systems; $N_2$: number of prospective systems; $N_3$: number of confirmed systems.

systems of multiplicity $M$.

The highest-multiplicity systems are listed in Table 3. For each system, the number of components (M1), number of optical components (Opt), and number of confidently hierarchical components (M2) are given. The system WDS 17457−2900 demonstrates the highest value of possible hierarchical multiplicity (7), while possible multiplicity of several other systems (WDS 23061+6356, WDS 17378−1315, WDS 10174−5354) reaches higher values, but it should be confirmed by observations.

It can be seen that these values are still far from those expected from theoretical predictions. Several possible ways can be considered to explain such a mismatch.

First, the theoretical possibility to construct a system with 8–9 hierarchy levels is based on purely geometrical considerations and does not necessarily mean that
Table 3. Systems of highest prospective multiplicity

| ID           | M1 | Opt | M2 |
|--------------|----|-----|----|
| WDS 23061+6356 | 31 | 8   | 1  |
| WDS 17378−1315 | 30 | 2   | 1  |
| WDS 10174−5354 | 29 | 3   | 2  |
| WDS 10451−5941 | 28 | 6   | 1  |
| WDS 15326−5221 | 25 | 0   | 1  |
| WDS 17457−2900 | 21 | 0   | 7  |
| WDS 01030+6914  | 18 | 1   | 1  |
| WDS 05353−0522  | 18 | 0   | 1  |

M1: number of components without optical ones; Opt: number of optical pairs; M2: possibly confident hierarchical multiplicity.

physical conditions in a protostellar cloud can permit to construct such a system. Consecutive fragmentation of a large contracting interstellar cloud is needed for a very high multiplicity hierarchical system to be born.

Also, very wide binaries ($a \geq 100$ AU) are so weakly bound that they can be effectively disturbed, even disrupted, by extremely weak perturbations from inhomogeneities in the Galactic potential due to stars, molecular clouds, dark objects, or large-scale tides. Thus, the outermost components of a very high multiplicity hierarchical system will probably not survive on their orbits and leave the system.

Finally, Fig. 1 demonstrates that we probably underestimate hidden multiplicity of stellar systems, and the number of photometrically unresolved components is much higher than catalogued data predict.

4. CONCLUSIONS

To explain inconsistency in stellar multiplicity between rather high values predicted by theoretical considerations and observational lack of systems with multiplicity higher than six, we have studied principal catalogues of visual double stars: WDS, CCDM and TDSC. They contain data on very high multiplicity (up to 30 components and more), thought not necessarily hierarchical, systems, including moving groups and (mini-)clusters. To collect all available information on these systems, it was first necessary to make a thorough and accurate cross-matching of their components in the catalogues. Optical pairs, when known or assumed from the probability filter, were flagged and eliminated from the statistics, and information on photometrically unresolved sub-components was added.

Principal results of the current study are the following.

• a cross-identification catalogue of 551 stellar systems of multiplicity six and more;
• a list of systems, candidates to utmost multiple hierarchical systems;
• a procedure for cross-matching components of very high multiplicity systems (i.e., in crowded stellar fields), which also can be used for identification of objects in future surveys of binary/multiple stars (Gaia, LSST).

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