Astronomical and Astrophysical Transactions (*AApTr*), 2013, Vol. 28, Issue 1, pp. 63–72,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Physical properties of components in multiple stars and their dynamics

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Received 8 November, 2011

We have considered a few multiple stars which have a weak hierarchy: HD 40887, HD 76644 (ι UMa), HD 136176, HD 150680, HD 217675 (o And), HD 222326, and HD 284419 (T Tau). We have calculated the masses of components and orbital elements of the subsystems, using data from the literature and original observations by the 1.5-m Russian-Turkey Telescope RTT 150 at Tubitak (spectroscopic observations) and 6-m telescope BTA in the Special Astrophysical Observatory (speckle interferometry). We have determined the structure and multiplicity of the systems more accurately. For system HD 222326, the new component was confirmed, so the system is quadruple. The spectroscopic observations were used to obtain new estimates of the component masses. The speckle-interferometric data were attracted to calculate the orbital parameters for close subsystems. The orbital parameters were found by classical Thiele-Innes method and apparent motion parameter method developed in Pulkovo Observatory. To determine the dynamical stability of the systems, we have applied the well-known stability criteria for triple systems, as well as the numerical simulations of the N-body problem. The stability and instability regions were outlined within the set of orbital parameters and masses. The unstable scenario is probable for the quadruple system HD 76644. Other systems are probably stable. We discuss possible reasons to violate the stability. Also we discuss possible future efforts in studies of multiple stars.

Keywords: Multiple stars; Dynamical evolution; Stability

1 Introduction

It is well known that historically the configurations of multiple stars were separated into two types. Those are Trapezia-like (or non-hierarchical) systems and ϵ Lyrae (or hierarchical) systems. Systems of the first type are usually unstable (with some exotic exceptions – for example, Ducati orbit, see Fig. 1). Usually these systems could be found among very young stars where the multiplicity fraction is close to unity. Second-type systems are stable and motions in them are almost Keplerian.

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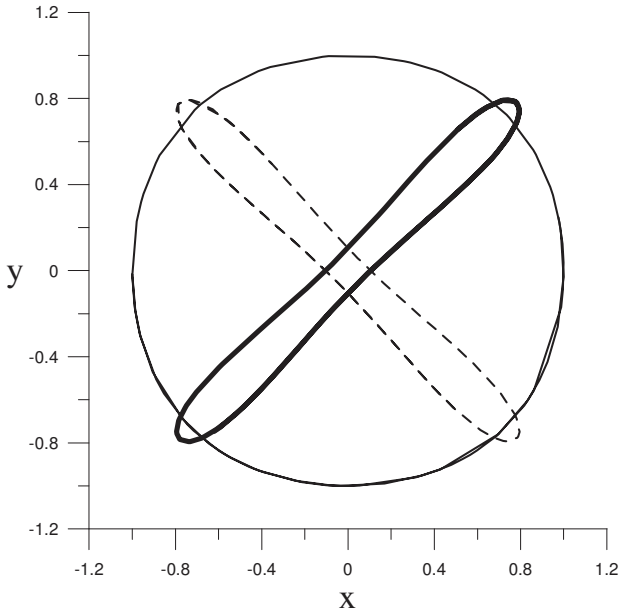


Figure 1 Stable Ducati orbit in a three-body problem. Note that the system is still non-hierarchical.

Also, there is an intermediate type of multiple stars – low-hierarchical systems. As an example of these systems we consider the quadruple system HD 40887 (see Fig. 2, [1]). Stability of such systems is always a special issue and needs a special investigation in each case.

As it was shown in earlier papers, some of these systems in the solar vicinity seem to be unstable both due to stability criteria and numerical simulations (see [2–4]). Of course, for most of those systems (if not for all) such a strange (for old stars) conclusion is a result of errors in orbital elements or physical parameters (e.g., masses). We have tried to investigate those systems to fix their properties and find out whether the "instability" result is artificial for all objects under study or there are really unstable systems among them. At the same time not only dynamical, but also physical parameters were determined.

So the objects of our study are multiple low-hierarchical systems with known orbital elements, for which instability was suspected.

2 Methods and observations

To examine a system's orbital elements, one of the classical methods — astrometry, spectroscopy or speckle interferometry – is usually used; at the same time, spectroscopy is the main method to determine the component's physical parameters. But for the systems under study neither of them could bring fair results, especially in

physical characteristics. Wide subsystems are too wide to study them as classical SB and still too narrow to get spectra (or photometry) separately for each component.

The only way to investigate such kind of objects is to use a combination of different methods and approaches to reconstruct the system's portrait. And the process itself is mostly iterational.

We used all available archive information about our systems to make the "first iteration" of their portrait as well to make a conclusion about their variability (magnitude, spectral, radial velocity, etc).

In addition to archive data, new observations have been performed. We used the 6-m BTA of Special Astrophysical Observatory of the Russian Academy of Sciences telescope to get speckle interferometric data, both relative position of the components (ρ, θ) and magnitude difference Δm. Diffractional limitation for BTA is about 20 mas, Δm limitation is about 6^m. Several filters centred from 5500 to 8000 Å were used and their widths varied from 40 to 100 Å. An EMCCD camera was used as a detector [5].

The 1.5-m Russian-Turkish telescope RTT150 (Tubitak National Observatory, Turkey) was used to get the spectra of low ($R = \lambda/\delta\lambda \approx 500$), medium ($R = 2500$) and high ($R = 40000$ and more) resolution [6, 7]. The $R = 500$ spectra were used for spectrophotometry to reconstruct complex SED of the system. After the standard reduction out-of-atmosphere fluxes were compared with one of artificial multiple stars, made of a sum of spectrophotometrical standards, weighted due to individual component's brightnesses. So, we have got some representation of component's spectral classes. Of course, formally the procedure is incorrect, but it led us to get at least some useful limitations for component's temperatures and relative brightnesses. Medium and high resolution spectra were used for mass, temperature, gravity determinations and radial velocity monitoring. For those we used the method of synthetic spectra and some standard spectral calibrations.

3 Results of studies of individual systems

For seven systems (HD 40887, HD 76644 (ι UMa), HD 136176, HD 150680, HD 217675 (o And), HD 222326, and HD 284419 (T Tau)) instability was suspected. So, whether they are stable or not, all of them need to be studied more intently to confirm instability or to refute it and to improve system's parameters, physical and/or dynamical. Hereafter, we'll give a short reconstruction of system's portraits, but sometimes those "puzzles" still need to be united in a joined picture.

Note that only multiples with all subsystems parameters determined are presented here. Reviews of probably unstable systems without determined subsystems are given in [8]. For two systems (HD 136176 and HD 150680) the results of component's parameter's determination are still in preparation. For HD 284419 (T Tau) only dynamical studies and orbital solution improvements have been performed.

- HD 40887. The system had been known as a triple until 2005, when the fourth component was discovered at VLT [1] (see Fig. 2 taken from it). Further positional and spectral observations are needed to improve orbital elements, which are certain only for the AB subsystem. At the same time, eccentricity and period of the wide pair (AB–CE) have a critical influence on system's dynamics.

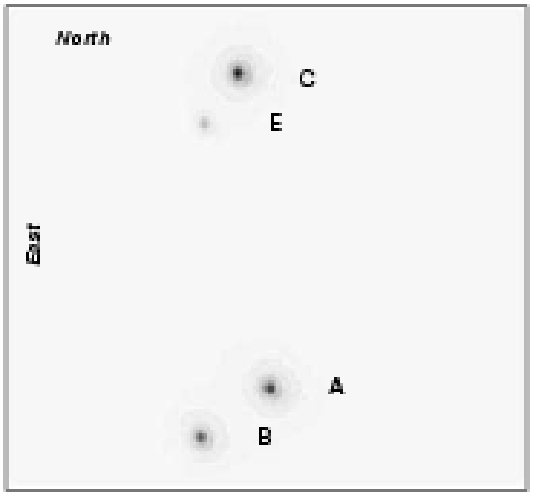


Figure 2 Low-hierarchical quadruple system HD 40887 at 2.12 μm.

We have made an attempt to improve orbital elements using new data from WDS and L. Berdnikov's observations in 2009. According to the recent work, the wide subsystem has a period of around 525^y and $e = 0.2$. In that case the system is still unstable (see Fig. 3), but uncertainty in parameters does not lead us to make a definite conclusion about its stability. At the same time, both the inner orbit of the CE pair and physical parameters of all components need to be improved. For example, anomalous "blue" (J–K) = 0 color of the faintest component E [1] is in contradiction with its magnitude.

A more refined analysis of this system's properties is the subject of separate work.

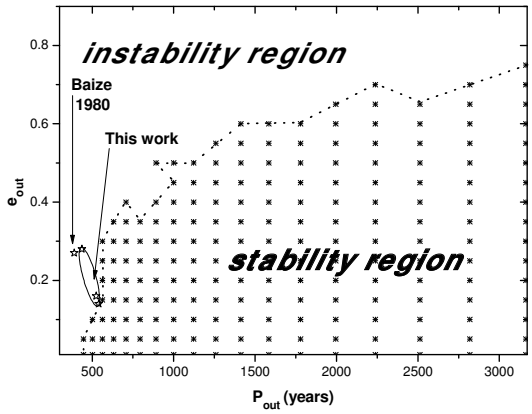


Figure 3 Stability and instability regions for HD 40887. All the other parameters (except $a_{\rm out}$ and $e_{\rm out}$) are fixed [1].

- HD 76644. The observational period for this system has lasted for nearly 200 years. The main component of the wide pair is quite bright ($v = 3.1^m$), but since 1830 and until 1980, separation decreased from $10''$ to $2''$ and this fact together with a large magnitude difference ($\Delta v \approx 7^m$) put the system under the limit of observational techniques (classical astrometry or speckle interferometry) at the end of the 20th century. In 1903, the B-component was resolved as a double by Aitken [9]. So, the system was known as a triple (with few centuries and 40^y period subsystems) until 1965, when Abt [10] discovered the radial velocity variability due to the existence of the fourth component; the period of the new (Aa) pair was preliminary defined as 4028^d. The wide (Aa–BC) pair period was calculated by Hopmann [11] to be 818^y.

  The defined system's parameters led us to the conclusion that the system should be unstable at a relatively short (less than 1 Myr) timescale [4] and encouraged us to more definite determination of the system's parameters.

  The analysis of physical parameters, orbital elements, and dynamical stability for the multiple star ι UMa has been performed. The data of astrometric observations from the WDS Catalogue and original observations taken with the BTA 6-m telescope and the RTT150 1.5-m telescope were used. In 2009, using the speckle interferometer of BTA we have resolved ι UMa as a triple for the first time since 1983.

  According to the current work the primary component A has the following parameters: $sp = F0\ V - IV$, $M = (1.7 \pm 0.1)\ M_\odot$, $T_{\rm eff} = (7260 \pm 70)$ K, $\log g = 4.30 \pm 0.07$. The secondary component in the close subsystem Aa is probably a white dwarf of mass $(1.0 \pm 0.3)\ M_\odot$. The spectral types and masses of subsystem BC components are $M3\ V$, $M4\ V$ and $(0.35 \pm 0.05)\ M_\odot$, $(0.30 \pm 0.05)\ M_\odot$ correspondingly. The total mass of the system is $(3.4 \pm 0.4) M_\odot$. The subsystem Aa has probable period $4470^d = 12.2^y$ and eccentricity of about 0.6. The outer subsystem has probable period about 2084^y and eccentricity about 0.9 (see Fig. 4). Using computer simulations and stability criteria, we show that the improvement of system's parameters does not change the conclusion about the dynamical evolution of the system. It remains unstable for reasonable parameter variations at time ranges less than 10^6 years with a probability larger than 0.98.

- HD 136176 is triple. Wide pair was observed since 1840 and first orbit constructed by Heintz [12] ($P = 203^y, a = 1.216''$) and current solution by Soderhjelm have nearly the same parameters ($P = 200^y,\ a = 1.22''$) and orbit solution is reliable, however inner binary (with $P = 50^y, i = 90^\circ$, according to Muller's (O-C) perturbations investigation [14]) may have significant errors. At the same time the third "Muller's" component is too faint to appear in optical spectra of the system. Our recent spectral observations together with the analysis of archive data do not confirm the presence of the third component, so the system is probably double. For the A-component we have got preliminary parameters $T_{\rm eff} = 5960 \pm 100$, $\log g = 4.3 \pm 0.1$ and $Z = -0.1 \pm 0.1$. Studies will be continued.

- HD 150680 is an astrometric triple system whose faintest component was found by analyzing perturbations [15] and observed only once in infrared [16]. This

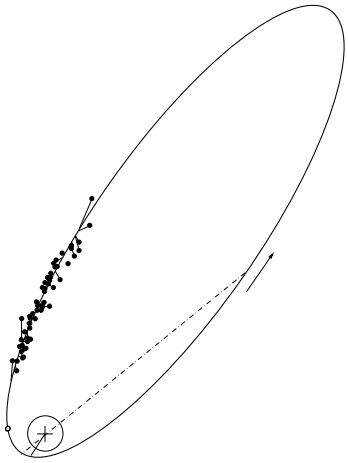


Figure 4 Apparent ellipses of relative $Aa - BC$ orbit of ι UMa. Open circles – SI BTA observations (2009–2010). Solid line – periastron direction, dash-dot line – node line. A $1''$ circle around the main component is shown. North is at the top, East is on the left.

inner orbit with 10.5^y cannot be considered as reliable. The outer orbit with $P = 34.5^y$ (pair with separation 1.3" has spectral classes ($G0\ IV\ +\ G7\ V$)) is much more definite. Infrared speckle interferometry is strongly desirable for this system.

- HD 217675. Analysis of physical parameters, orbital elements and dynamical stability for the multiple Be star HD 217675 (o And) has been performed using the observations taken with the BTA and the RTT150.

  The history of the spectroscopic study of this bright ($v = 3.6^m$) system spans more than 100 years. In 1949, the system was resolved as a double [9], in 1975 the third component was marginally detected [17], and in 1987 Hill interpreted the spectral evolution of some line profiles as SB display [18], so o And has "become" a quadruple.

  As suggested in previous works [19, 20], the orbital and physical parameters led us to the conclusion about the probable instability of this system [3]. So we were going to improve those parameters and to confirm or to contradict this result at the higher level of precision.

  In our work we have shown that the system configuration "2+2" (in contradiction with [19]), where one of the inner subsystems is a spectroscopic binary with a period of 33.0026 ± 0.0004^d, while the outer subsystem has a period of 117.4 ± 1.6^y. The total mass of the system is $(18 \pm 2)M_\odot$.

  Parameters of the second inner subsystem BC are defined uncertainly, a preliminary solution gives us a period of 5.7^y. So it is impossible to make a final modelling of the dynamical evolution of the system, but three-body analysis of the dynamics of the system shows that the system is stable.

- HD 222326. The orbit of this 7.6^m triple system was constructed first by Heintz [21] in 1967 with $P = 292^y$ and since that time several attempts have been made to improve it. In 1986, McAlister [22] discovered a third body in the system using speckle interferometry. We have shown [3] that the system should be unstable with the parameters determined for it by early authors. In this

Table 1 Physical parameters of HD 222326 components.

Component	$T_{\rm eff}$, K $\sigma_{T_{\rm eff}}$, K	$M_{\rm vis}$ $\sigma_{M_{\rm vis}}$	M, $M_\odot$ σ_M, $M_\odot$	sp
A	$5.7 \cdot 10^3$	0.93	1.2	G0III
	$4 \cdot 10^2$	0.2	0.3	
B	$6.6 \cdot 10^3$	1.06	1.3	F3III
	$4 \cdot 10^2$	0.2	0.3	
C	$> 2 \cdot 10^4$	1.91	0.7	sdO-BVIII
		0.2	0.4	

work the physical and dynamical parameters of this multiple system have been reexamined. The velocities V_r for individual components of HD 222326 and for the system as a whole were also determined using high-resolution spectra (see Table 1). For subsystems we have got improved orbital solutions based on speckle interferometric observations (see Fig. 5). The periods of inner and outer subsystems are 23.6^y and 341^y, respectively. In combination with other orbital parameters and masses, our analysis of dynamical evolution of HD 222326 using the numerical integration and stability criteria shows that this system is stable at a timescale $\geq 10^6$ yr. A combination of spectral and speckle observations led us to determine preliminary positions of components on the H–R diagram and

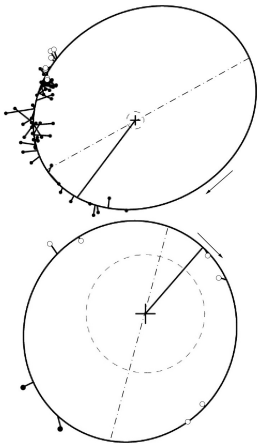


Figure 5 HD 222326 subsystems orbits. Upper: outer subsystem HD 222326A-BC, lower: inner subsystem HD 222326B-C. Central circle radius is $0.02''$ (BTA difractional limit). Open circles – BTA observations, filled – all other points. Solid line – periastron direction, dash-dot line – node line.

their masses. Probably, all components were evolved and left the MS at the H–R diagram, component C seems to be the blue compact object sdO-B. The presence of the fourth component in this system is also suggested because V_r variations are too fast even for the 15^y period.

- HD 284419. This young object in the pre-main-sequence stage was discovered in 1852 by Hind during studies of the nebula NGC 1555.

  Speckle interferometry carried out in 1982 demonstrated that this is a binary system (the wide pair $T\ Tau_N$ and $T\ Tau_S$, separated by $0.6''$) [23], with the southern component $T\ Tau_S$ being brighter in the infrared and essentially unobservable in the visual, with $V > 19.6^m$ [24]. In 2000, Koresko [25] resolved $T\ Tau_S$ into two objects, separated by $0.05''$.

  For this system, considered to be a triple (see discussion in [26], for example) detailed studies of orbital parameters were carried out. The parameters of the apparent motion method are used to obtain new orbital solutions for this system. The regions of dynamical stability of the system as functions of the orbital parameters are estimated because it is impossible to determine a unique solution for the orbit with the available data. For periods shorter than 300 yr and longer than 5500 yr, the probability of decay of the system on timescales less than 10^7 yr is greater than 95%. This conclusion is supported by the application of the stability criteria, as well as direct modelling of the systems dynamical evolution.

  The question of the stability of the T Tau system remains open, and a complete answer to this question cannot be obtained without elucidating the multiplicity of the system and a more precise determination of the component's physical parameters.

4 Discussion and conclusions

The main conclusion of current work is evident – necessity and efficiency of an integrated approach for the systems with some kind of "unexpected" results (e.g., instability for "old" systems).

Another result is that a number of orbital elements and component's parameters were improved during the study.

And the most interesting one is the existence of the old multiple systems with decay time less than 1 Myr in the solar vicinity. One can suggest several reasons to explain it: final stage of inner dynamical evolution ("evaporation") of the minicluster, encounters with massive objects of the Galactic field and moving groups, temporal capture of the field star by a binary or multiple system, merging of components in a close multiple system.

We have roughly estimated [3] the expected number of unstable systems within the solar neighborhood of two hundred parsecs due to the last three mechanisms. The expected number of unstable systems within a sphere of 200 pc around the Sun for different scenarios is about 1–10 ($P_{\rm out} < 10^3$ yr). This is not negligible.

This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory, and the authors are grateful to the WDS team and

personally to B.D. Mason for help with data. Work was performed with partial support of RFBR projects 12-02-00185-a, 10-02-01145-a, 12-02-97006-r-POVOLZHYE-a and President Programme for Support of the Leading Scientific Schools (project # 3290.2010.2).

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