VISUAL BINARY STARS: DATA TO INVESTIGATE FORMATION OF BINARIES

D. Kovaleva, O. Malkov, L. Yungelson, D. Chulkov

Institute of Astronomy, Russian Acad. Sci.,
48 Pyatnitskaya St., 119017 Moscow, Russia; dana@inasan.ru

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Abstract.
Statistics of orbital parameters of binary stars as well as statistics of their physical characteristics bear traces of star formation history. However, statistical investigations of binaries are complicated by lacking or incomplete observational data and by a number of observational selection effects.

Visual binaries are the most numerous observed binaries, the number of pairs exceeds 130000. The most complete list of presently known visual binary stars was compiled by cross-matching objects and combining data of the three largest catalogues of visual binaries. It was supplemented by the data on parallaxes, multicolor photometry, spectral characteristics of the stars of this list taken from other catalogues. This allowed us to compensate partly for the lack of observational data for these objects. Combined data allowed us to check validity of observational values and to investigate statistics of the orbital and physical parameters of visual binaries. Corrections for incompleteness of observational data are discussed. Obtained datasets and modern distributions of binary parameters will be used to reconstruct the initial distributions and parameters of the function of star formation for binary systems.

Key words: Visual binary stars – astronomical catalogues and databases

1. INTRODUCTION

Binary stars are a significant component of stellar population that can be observed via a number of methods giving a variety of data. Statistics of parameters of binary systems first became subject of interest back in 1920–1930s (Opik 1924, Kuiper 1933, Aitken 1935, Ambartsumian 1937, etc.); it was repeatedly revisited in 1970–1980s when new challenging results had been obtained, and remains a matter of discussion currently, since the new methods and observational techniques allow us to register more binaries: distant binaries, binaries with fainter components, closer located components, more remote components (Abt & Levy 1976, Vereshchagin et al. 1988, Kraicheva et al. 1989, Duquennoy & Mayor 1991, Poveda et al. 1994, 2007, Patience et al. 2002, Abt 2006, Kouwenhoven et al. 2008, Rahgavan et al. 2010, Duchêne & Kraus 2013, Tokovinin 2014, Tokovinin & Kiyaeva 2016, etc.).
It is accepted that the statistics of orbital parameters of binary stars as well as the statistics of their physical characteristics may bear traces of star formation history (see, for instance, Poveda et al. 2007, Tokovinin & Kiyaweva 2016). These traces are, however, substantially distorted by evolution and by the effects of observational selection. The components of so-called wide pairs do not affect each other in the course of physical evolution, and orbital parameters of such pairs evidently remain almost unchanged (the unique active agent is mass, while angular momentum loss via stellar wind is significant for giants only). This makes investigation of distributions of wide pairs over various characteristics a rather attractive task.

In the modern investigations of statistics of binaries, one may observe three different approaches and, sometimes, their combination. Namely, some authors consider datasets declared to be volume-limited; some choose uniform datasets like those in clusters and associations; some simulate observations based on theoretical considerations and compare the result to observational data. Every approach has its advantages and its flaws, and obviously the complete picture may come as the result of their combination. In this work, we present datasets compiled to be modelled by population synthesis methods to solve the inverse problem of reconstruction of initial parameter distributions of binary stars.

The majority of wide pairs are observed as visual binaries. The number of known catalogued visual pairs (those that can be resolved using a telescope) exceeds 130000. Recently, a new comprehensive set of data on visual binaries named WCT was compiled by Isaeva et al. (2015) by cross-matching data from the current version of The Washington Visual Double Star Catalog (WDS, Mason et al. 2014), the Catalog of Components of Double & Multiple stars (CCDM, Dommanget & Nys 2002), and the Tycho Double Star Catalogue (TDSC, Fabricius et al. 2002). Additionally, the WCT contains parallaxes for more than 14000 pairs, mainly from Hipparcos data (and the rest from SIMBAD). The WCT catalogue (together with WDS, CCDM and TDSC) was uploaded into the Binary stars database, BDB (Kaygorodov et al. 2012, Kovaleva et al. 2015a). A statistical investigation of the WCT data was described by Kovaleva et al. (2015b). In this paper, we present solution of some problems we encountered, as well as add and analyze data to complete construction of the set of data for modelling.

In Section 2, we discuss what can be said about the distribution over periods for wide pairs based on visual binaries data. In Section 3, the refinement of spectral classification process and results are described. In Section 4, we discuss obtaining distributions over physical parameters of the components. In Section 5, the results of investigation of the visual binary star data are summarized.

2. DISTRIBUTION OF WIDE BINARIES OVER PERIOD

The distribution of wide binaries over the period/semimajor axis of their orbits reflects the process of their formation and can help to understand the latter. In general, two possibilities are discussed: the power-law \( f(a) \propto a^{-\alpha} \) (which is, in the case of \( \alpha = 1 \), the well-known Ōpik’s distribution) and the Gaussian-like law in respect to \( \log P \) or \( \log a \). Ōpik’s distribution is an indicator of the energy relaxation process involving interaction of multiple bodies, which suggests binary formation preferably or exclusively in multiple systems (Poveda et al. 2006).

After refining our dataset by removing erroneous data of various kinds, optical
Fig. 1. Period estimates for the same wide binaries obtained by different couples of positions (based on data for 8000+ binaries with three and more positions). Grey dots are within the sector where $P_2 = P_1 \pm 50\%$; this sector contains 80% of all points.

pairs, rounded-up data, multiples, etc. (see discussion in Kovaleva et al. 2015b), some 47500 pairs having two and more different valid observations of relative positions of the components at different epochs remained. For more than 8000 of them, three or more observations are available. This allows us to estimate average angular velocity of the visible orbital motion and thus, to extrapolate it to a rough estimate of the orbital period. Let us note that, unlike visual binaries with calculated orbits, the probability for a star to be observed as a visual binary is related to the period value only for the closest and for the most remote pairs, while in the wide range of periods it does not depend on the period. Evaluation of the angular velocity of visible orbital motion does not require parallax and thus can be performed for all the 47500 pairs of our dataset.

The internal scatter of such an estimate can be determined for the same binaries using different pairs of positions where it is possible. Figure 1 represents the estimates of period for the same wide pair obtained for two positions in the WDS catalogue vs. one position in the WDS and one non-matching WDS position from TDSC. 80% of points are located within $P_2 = P_1 \pm 50\%$ sector (grey dots). The orbital periods for almost thousand pairs of our dataset can be found in the ORB6 catalogue of orbital elements (Mason et al. 2001). Thus, we can compare our rough estimates for these binaries to the period values obtained from orbital solutions. For this comparison, we excluded primary pairs of multiple systems to avoid pair identification problems, and pairs with periods less than 10 years because the method is not applicable for such short-period pairs. One cannot determine from
Fig. 2. The difference between orbital and estimated period for the same binaries vs orbital period (based on the data for 833 binaries with orbital periods ≥ 10 yrs found both in the refined WCT dataset and in the ORB6 catalogue).

two or three observations whether they refer to the same orbital cycle (as we presume in evaluations). This makes our estimates systematically larger than orbital periods even for the binaries with $P \geq 10$ years, but the estimate for shorter periods is always non-realistic. This limits the dataset down to 833 binary stars with periods of 10 years or longer.

Figure 2 represents the absolute value of the difference between the values of orbital periods (obtained from orbital solution) and periods roughly estimated from angular orbital velocity, vs. orbital periods. This gives us an estimate of the typical error range for the method of getting period from the angular orbital velocity. It appears to be approximately ±40 years for periods shorter than 100 years; about ±100 yrs for $200 \leq P \leq 500$ years; and about ±600 yrs for the range of periods between 1000 and 2000 years.

Figure 3 displays the cumulative distribution over estimated periods for the pairs of the refined dataset from the WCT. For comparison, the distribution of all the binaries of ORB6 over the period is also shown.

3. VERIFICATION OF THE SPECTRAL CLASSIFICATION

The WCT catalogue includes spectral classification for about 63000 binaries, while luminosity classes necessary to estimate physical parameters of the components such as luminosities (if the distance is unknown) and masses are available for less than a half of this set. The refined WCT dataset does not include pairs
with degenerate or other peculiar-type components. For other stars, since mainly only the spectral type of the primary or combined spectrum is known, we consider this available spectral type as that of the primary and expect that the secondary has the same or fainter luminosity class (Kovaleva et al. 2015b).

The investigation of the binaries with primaries’ luminosity class V in combination with trigonometric parallaxes for these stars, when available, demonstrated, however, that for this dataset as a whole (containing 4059 binaries) absolute luminosities, determined by trigonometric parallax taking into account interstellar extinction, were systematically larger than their absolute luminosities prescribed by the luminosity class and spectral type combination. This suggested that the dataset might actually contain stars of luminosity classes other than V that contaminate data statistics, and forced us to reconsider spectral classifications using alternate sources of data.

We have tested the data on spectral classification within the WCT catalogue noticing discrepancies between WDS, CCDM, and TDSC data, and checked the WCT dataset spectra in the SIMBAD database, as well as in the modern catalogues containing spectral classification (5268 pairs found in McDonald et al. 2012; 192 pairs identified with the NStars catalogues, Gray et al. 2003, 2006). As the result of this search, we found and corrected erroneously attributed luminosity classes for 68 of about 1600 giants (luminosity class III) and for 77 of about 4000 dwarfs (luminosity class V) with known trigonometric parallaxes. Thus, we have compiled a dataset containing 5731 binary stars with confirmed luminosity class and known trigonometric parallaxes, including 4049 pairs with main components having luminosity class V and 1682 pairs with main components of class III.

Fig. 3. Distribution over the period $P$: the solid line is for the refined WCT dataset and the dashed line, for all ORB6 periods.
Fig. 4. Distribution over the mass ratio $q$ obtained for the binaries with main components of luminosity class V and known trigonometric parallaxes. The dashed line is for the complete available sample of 4049 binary stars and the solid line, for the restricted sample of 892 binaries. The restricted dataset avoids regions of observational incompleteness in the $(V_1, V_2, \Delta V, \rho)$ space of parameters.

4. DETERMINING CHARACTERISTICS OF THE COMPONENTS

For the set of 4049 pairs with confirmed luminosity class V and known trigonometric parallax, we obtain bolometric luminosities from visible magnitudes, parallaxes, interstellar extinction $A_v$ estimated using the cosecant law (Parenago 1940), and $M_v - \log L_{bol}$ calibrations for dwarfs from Pecaut & Mamajek (2013), Mamajek (2016). We avoid using multicolor photometry from SIMBAD or estimates of $\log L_{bol}$ by McDonald et al. (2012) available for the majority of the sample because it is mainly uncertain whether it refers to the main component or to the binary star as a whole.

We determine regions of observational incompleteness in the space of parameters $(V_1, V_2, \Delta V, \rho)$, as described in Kovaleva et al. (2015b). The chance for a star to be detected as a visual binary depends on the visible distance between the components, magnitude of the primary, and magnitude difference. We restrict our dataset to $\rho > 1$ arcsec, $V_1 < 8.5^m$, $V_2 < 10.5^m$, $\Delta V < 4^m$, to avoid regions of the space of parameters where it is obviously incomplete. This “restricted” sample contains 892 binary stars.

Figure 4 presents the mass ratio of the components, $q = m_2/m_1$, we obtain for pairs with confirmed luminosity class V and known trigonometric parallax. The black dashed broken line refers to the complete set of 4049 pairs, while the grey solid broken line represents data for the restricted sample of 892 binary stars. For this last sample, the mass ratio distribution looks flat for $q \geq 0.5$. 
5. RESULTS: DATASETS FOR MODELLING FORMATION HISTORY OF WIDE BINARIES

As the result of cross-matching, analysis, and investigation of the data for visual binary stars, several datasets have been compiled for modelling the present-day distributions of wide binaries over various parameters. For various datasets, the distributions over orbital periods, semimajor axes, absolute magnitudes, bolometric luminosities and masses of components were constructed (Kovaleva et al. 2015b; this paper). The dataset of 892 pairs was corrected for selection effects on stellar magnitude, magnitude difference and angular separation between the components. It is still distorted by evolutionary effects and is not volume-complete. This dataset allows us to consider some current distributions of wide binaries on physical characteristics within a certain range of parameters. The dataset of 573 pairs (4049 binary stars with primaries of luminosity classes V and 1682 binaries with primaries of class III) with known physical characteristics of the components permits to model the observed distributions of binaries over observational and physical parameters. The dataset of 47500 pairs, with several reliable relative positions of the components measured, will be used to model the distribution over observed medium angular velocity of orbital motion of the pairs, to discriminate between possible models of distribution of binaries over orbital periods. The dataset of about 102000 pairs refined by removing erroneous data, optical pairs, rounded-up data, multiples, etc. will be used to develop a statistical error model.

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