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Orbital binaries in Gaia: parallaxes and masses

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Abstract. We have compiled the most comprehensive list of orbital binaries (visual binaries with known orbital elements) with *Gaia* DR2 parallaxes and have calculated dynamical masses for more than 2000 pairs. Distributions of the orbital binaries on mass and observational parameters are constructed and discussed.

Key words. Binaries: orbital – Binaries: visual – Catalogues

1. Introduction

Orbital binary stars (visual binaries with orbit solutions) are essential objects for determining dynamical and physical properties of stars, through a combined analysis of photometric and astrometric data. Along with double-lined eclipsing binaries, orbital binaries with known distances are the only types of binary systems that enable one to determine stellar masses and semi-major axes of orbits. However, orbital binaries are by an order of magnitude more numerous than double-lined eclipsing binaries.

The main goal of this work is to estimate dynamical masses of orbital binaries. It builds on our previous work (Malkov et al. 2012; Tamazian et al. 2016; Docobo et al. 2016), however, in the current study we use much more numerous and precise *Gaia* DR2 (Gaia Collaboration et al. 2018) trigonometric parallaxes.

Section 2 contains a description of the orbit list compilation procedure. Cross-matching of orbital binaries with *Gaia* DR2 is described in Section 3 while dynamical masses are computed and discussed in Section 4. Finally, in Section 5, we draw conclusions.

2. The orbit list compilation

In this section we describe the procedure of list compilation. We base our study on the ORB6 catalogue (Sixth Catalog of Orbits of Visual Binary Stars, Hartkopf et al. 2001), which is updated constantly. We have taken all orbital binaries from ORB6.

Another large collection of orbital binaries is the OARMAC catalogue (Catalogue of Orbits and Ephemerides of Visual Double Stars, Docobo et al. 2001) (the latest version dates from 2013). Our comparison of ORB6 and OARMAC reveals four orbital binaries appearing on OARMAC and absent in ORB6. We have included them in our study. These are WDS 04375+1509 (Olevic & Cvetkovic 2003) WDS 09174+2339 (Hopmann 1973) WDS 21068+3408 (Arend et al. 1963) WDS 21124-1500 (Hopmann 1974) Orbital elements for WDS 09174+2339 and WDS 21124-1500 were taken from original publications, not from OARMAC. Missing cross-identification was taken from Simbad. Secondary magnitude for WDS 04375+1509 was taken from WDS. In all four cases we put quality grade equal to 5 (see quality grade discussion in the ORB6 description). The following note for WDS 21124-1500 is given in (Hopmann 1974): the poor material permits 2 solutions. There is a) either an optical pair, b) or a parabolic encountering pair of faint main-sequence stars with plx=0.”15, q=129 AU.

Primary magnitude for two systems (WDS 17367+6934 and WDS 17422+3804) are absent in ORB6, and they were added from Simbad. Period values for three systems are absent in ORB6, and they were added from literature: WDS 02124+3018 (Kaye et al. 1995), WDS 02556+2652 (Tokovinin 2018), WDS 15567-4219 (Biller et al. 2012).

So, the primary brightness and period is given for all systems in our list. The only exception is WDS 21124-1500, its period is undefined as it is apparently a parabolic pair (see above).

The resulting list (hereafter List3000) contains 2946 orbits for 2848 pairs: 2773 pairs have a single orbit, 61 pairs have two orbits, 10 pairs have three orbits, 1 pair has four orbits, 1 pair has five orbits, and 2 pairs have six orbits. Those 2848 pairs combine into 2270 binaries, 115 triples, 14 quadruples, and 1 quintuple. Beside that ORB6 contains orbits for 42 stars orbiting Sgr A*, and we removed them from further consideration.

To carry out a statistical analysis of orbital binaries with high quality orbits, one needs to “refine” the resulting orbit list. Poor-quality orbits and astrometric orbits (ORB6 quality grades 4, 5 or 9) were removed from the refined list.

This refined list (hereafter List1000) contains 1033 orbits. 15 systems in List1000 are triples, other 1003 are binaries. Among them, one pair (WDS 06418+3041) has two orbits.

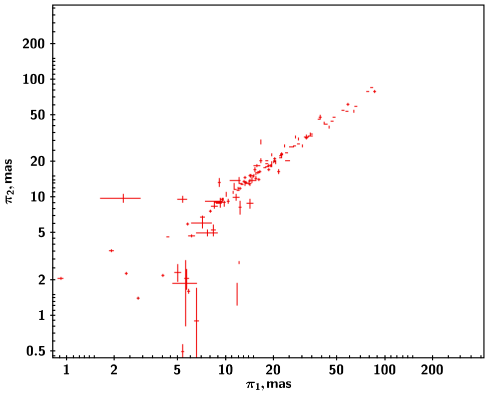

Fig. 1. Parallaxes of components of orbital binaries, when both are available in *Gaia* DR2.

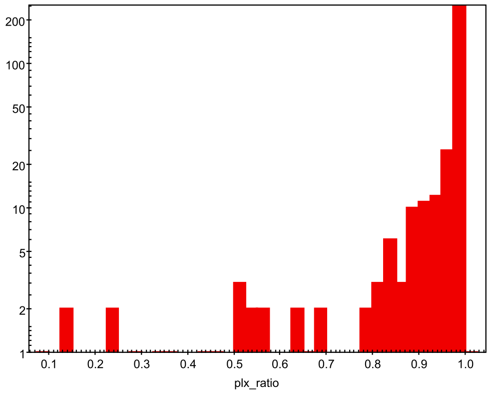

Fig. 2. Components’ parallax ratio for orbital binaries, when both parallaxes are available in *Gaia* DR2.

3. Cross-matching with *Gaia* DR2

We have conducted a cross-matching of List3000 objects with *Gaia* DR2. The criteria of the matching were the following: matching radius is 3 arcsec, magnitude difference limit is 1.5 mag. However, there were not strict criteria, and we had been reducing the requirements if an ORB6 object and its potential *Gaia* DR2 counterpart demonstrated, i.e., a similar proper motion. In a case when more than one *Gaia* DR2 object fell into the matching circle, positional information based on the ORB6 and WDS ephemeris, was taken into account.

For 15% of List3000 pairs both components were found in *Gaia* DR2, for 72% *Gaia* DR2 contains only one (primary or combined) light, and 12% were not found in *Gaia* DR2. Hereafter in this Section we call these three samples Gaia2, Gaia1 and Gaia0, respectively. An additional criterion was applied to cases, when *two* objects fall in the matching radius (i.e., Gaia2 case): their angular separation should not exceed a twofold angular separation ρ of a matching List3000 pair.

Orbital periods P of List3000 pairs vary from 2.23×10^{-3} to 3.7×10^{6} yr, and semi-major axes a vary from 1.6×10^{-4} to 1.13×10^{4} arcsec. Gaia2 sample demonstrates that *Gaia* can detect and measure both components of a pair if it is not closer than $P = 8.6$ yr and $a = 0.16$ arcsec. On the contrary, Gaia0 sample has upper limits $P = 3600$ yr and $a = 17.66$ arcsec, i.e., all pairs wider than these limits are represented in *Gaia* DR2 by at least one component.

As concerns the magnitude distribution, components of the List3000 pairs have brightness from -1.47 (Sirius) to 23.6 mag, and maximum magnitude difference dm is 14.5 mag. The fainter magnitude limit and the largest dm for Gaia2 objects are found to be 14.6 and 7.93 mag, respectively. It is worthy to note also that Gaia0 sample almost does not contain pairs with dm exceeding 2 mag, i.e., more "contrast" pairs are always represented in *Gaia*, at least by one component. A few exceptions are five very bright ($m < 3$ mag) pairs and the faintest pair in List3000 (WDS 18483-6856, 23.6+20.9 mag).

We have found that *Gaia* DR2 always provide parallaxes for *both* components, if a(arcsec) $> 5\times dm + 1$. We have found also that if the primary parallax exceeds 30 mas, than the secondary parallax is always known.

Comparison of components' parallax for Gaia2 objects demonstrate a satisfactory agreement (see Fig. 1). Few exceptions are distant binaries. A distribution of parallax ratio is shown in Fig 2. It can be seen that the vast majority of pairs have the parallax ratio more than 0.77. A brief analysis of ORB6 data for the remaining pairs shows that at least some of them (WDS 15082+3958, WDS 23116+3654, WDS 08391-5557, WDS 23487+6453, WDS 07106+1543) are suspected to be optical pairs (though false cross-matching or erroneous *Gaia* parallax should not be ruled out). We found no correlation of the parallax ratio with brightness of the component or orbital elements, though all pairs with $dm > 2$ demonstrate parallax ratio no lower than 0.84 (with one exception, WDS 03342+4837). Also, parallax ratio for List1000 pairs is always larger than 0.8 (with one exception, WDS 03344+2428).

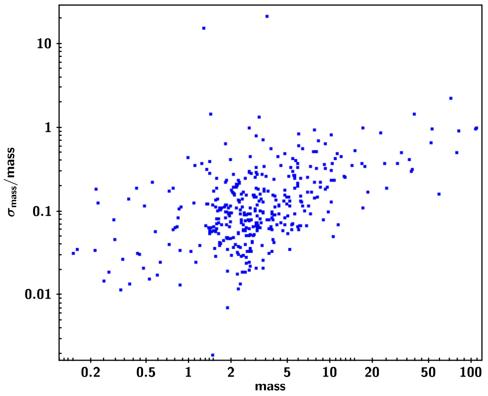

Fig. 3. Dynamical masses with their relative errors of orbital binaries with high quality orbital parameters.

4. Dynamical masses

Period and semi-major axis, combined with parallax, yield the total mass of the system (so called dynamical mass), according to Kepler's law:

$$M_d \equiv M_1 + M_2 = \frac{(a")^3}{\pi^3 P^2}, \tag{1}$$

where P is the orbital period (in years), $M_{1,2}$ are the components' masses (in solar mass), a" and π are the semi-major axis and the parallax (in identical units), respectively.

These dynamical masses were calculated for all pairs, where *Gaia* DR2 parallax is available. The majority of the resulting M_d values for high quality orbits (List1000) vary between 0.15 and 126.5 (hereafter in solar mass), they are plotted, with their relative errors, in Fig. 3.

In addition four pairs demonstrate unrealistically large dynamical masses ($M_d > 400$), and their mass uncertainty exceeds 120%. One more pair, WDS 20298+0941 AB has, on the contrary, rather small value $M_d = 0.0070 \pm 0.0002$. Note that WDS 20298+0941 AC, also included in our study, has quite reasonable and reliable value of $M_d = 0.214 \pm 0.007$. It apparently indicates that our estimate for WDS 20298+0941 AB is erroneous, and a possible reason for that can be an uncertainty in semi-major axis value and variability of the object (WDS 20298+0941 AB = HU Del, see discussion in ORB6 Notes).

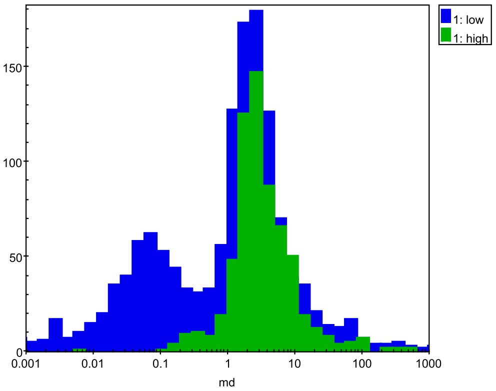

Fig. 4. Distribution of formal values of dynamical masses of orbital binaries with high (green) and lower (blue) quality orbital parameters. A peak at $M_d = 0.8$ is a result of a selection effect, it reflects the existence of the relatively large number of so called astrometric binaries (with one visible component, demonstrating nonlinear proper motion) in List3000.

Unrealistic masses are found more among lower quality orbit pairs, but the majority of them are also spread across a range of values between 0.3 and 20 solar mass (see distribution of formal M_d values in Fig 4).

5. Conclusions

We have cross-matched the most comprehensive list of orbital binaries with *Gaia* DR2 and calculated dynamical masses for more than 2000 pairs. Our estimates can be useful for study or particular objects. The resulting list is available upon request.

In further work the dynamical mass of the studied systems will be verified with value, estimated from luminosity, and value, estimated from spectral type, when available. The resulting distributions, after correction for selection effects, will allow us to make conclusions on the initial mass function and other properties of orbital binaries.

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