Wide Binaries in TGAS:
Search Method and First Results

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Abstract. Half of all stars reside in binary systems, many of which have orbital separations in excess of 1000 AU. Such binaries are typically identified in astrometric catalogs by matching the proper motions vectors of close stellar pairs. We present a fully Bayesian method that properly takes into account positions, proper motions, parallaxes, and their correlated uncertainties to identify widely separated stellar binaries. After applying our method to the $>2 \times 10^6$ stars in the Tycho-Gaia astrometric solution from Gaia DR1, we identify over 6000 candidate wide binaries. For those pairs with separations less than 40,000 AU, we determine the contamination rate to be $\approx 5\%$. This sample has an orbital separation (a) distribution that is roughly flat in log space for separations less than $\sim$5000 AU and follows a power law of $a^{-1.6}$ at larger separations.

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1. Introduction

Binary systems exist with orbital separations extending from $\sim$10 $R_\odot$ to $\sim$pc. Unresolved binaries at the smallest separations are typically found by identifying radial velocity variations indicative of orbital motion, while binaries at intermediate separations can be identified by observing the stars' motions through their orbits over many years (e.g., Raghavan *et al.* 2010). At the largest separations, pairs of nearby stars are typically identified as being in a binary by matching their proper motions; these common proper motion pairs have separations from 10^2 to $\geqslant 10^4$ AU (Luyten 1971).

Beyond $\approx 10^3$ AU, the components of wide binaries are not expected to interact significantly over their lifetimes. These pairs can be considered mini-open clusters (Binney & Tremaine 1987) and are uniquely powerful for answering questions that cannot be addressed by other stellar systems. For example, wide binaries consisting of white dwarfs, subdwarfs, or M-dwarfs with FGK main sequence companions have been used to calibrate metallicity scales and age-rotation relations (e.g., Lépine *et al.* 2007). Other white dwarf-main sequence pairs and double white dwarfs have been used to determine the initial-to-final mass relation for white dwarfs (e.g., Zhao *et al.* 2012). At the widest separations, the orbits of stellar binaries are dynamically affected by interactions with passing stars, giant molecular clouds, and the Galactic tide, each of which acts to stochastically disrupt them (Weinberg *et al.* 1987). These binaries have been used as probes of the gravitational potential of their host, including the contribution of dark objects and of dark matter in general (e.g., Yoo *et al.* 2004).
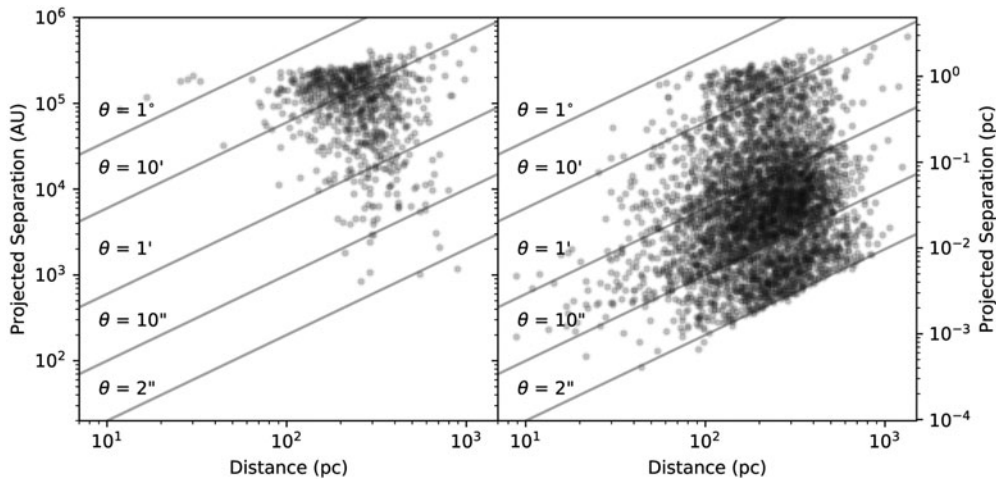
Figure 1. The distance and projected separation distribution of pairs from our random alignment catalog (left panel) and our catalog of >6000 candidate pairs (right panel). The locus of points at projected separations $\sim$1 pc are primarily random alignments since they exist in both panels. At separations less than $4{\times}10^4$ AU, there are few random alignments. Comparison between the two panels indicates that the contamination rate of random alignments in our sample of wide binaries is $\approx$5% for pairs with separations less than $4{\times}10^4$ AU.

Due to its extremely precise astrometry, the final *Gaia* catalog will produce accurate positions, proper motions, and parallaxes for more than a billion stars in the Galaxy. This data set offers a unique opportunity to robustly identify a sample of wide stellar binaries. Using the Tycho-*Gaia* Astrometric Solution (TGAS) from the first *Gaia* data release (Lindegren *et al.* 2016), we define a Bayesian statistical method that accounts for the correlated uncertainties in *Gaia*'s astrometry to identify wide binaries.

2. Method Overview

We identify stellar pairs using the five dimensions of phase space provided for each star in the TGAS catalog: right ascension (α), declination (δ), proper motion in right ascension and declination (μ_α, μ_δ) and parallax (ϖ).

We simplify the problem by reparameterizing the 10 observables (five for each star) into eight for each pair; instead of having a separate sky position and proper motion for each star, we use one position and proper motion for the stellar pair and include an angular separation (θ) and a proper motion difference ($\Delta\mu$) between the two stars. We then split the observables into one set containing the (α, δ) and (μ_α, μ_δ) position of the stellar pair, and another set containing the difference between the observed values for each of these parameters as well as the individual parallaxes (θ, $\Delta\mu$, ϖ_1, and ϖ_2).

Our method relies on a Bayesian formalism with two classes: every pair of stars is either a random alignment of unassociated stars or a genuine wide binary. For each stellar pair, we calculate two prior probabilities and two likelihoods. Since the number of stellar binaries in a sample scales with the size of the sample, N, while the number of randomly aligned pairs scales with $N(N-1)/2$, any arbitrary pair has a strong prior of being a random alignment. The exact value of this prior, which depends on the local density of a pair's position and proper motion, needs to be determined for every pair.

The probability of random alignments scales with the phase space volume of stars multiplied by the local stellar density in that phase space. Therefore, the random alignment
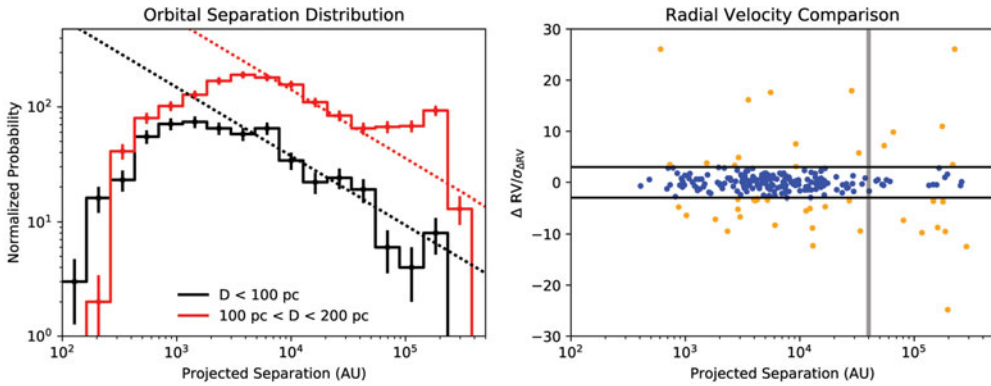
Figure 2. Left panel – The orbital separation distribution of our candidate pairs at distances less than 100 pc (black) and at distances between 100 and 200 pc (red). At large separations, the distribution scales with $a^{-1.6}$ (dotted lines), while at smaller separations, the distribution flattens and scales with a^{-1}. Right panel – Comparison between the radial velocities of the two stars in the subset of our candidate pairs observed by the RAVE survey. Most pairs have radial velocities consistent at the 3σ level (blue), bounded by the gray horizontal lines. Several pairs have somewhat discrepant radial velocities (yellow). Particularly for those pairs with projected separations less than 4×10^4 AU, these pairs could indicate the presence of unresolved binaries in our sample; some of our wide binaries may in fact be hierarchical triple systems.

likelihood increases linearly with θ and $\Delta\mu$, and scales with the local density in (α, δ) and (μ_α, μ_δ) space. Calculating the corresponding likelihood that a particular stellar pair is a genuine binary has traditionally been determined as the likelihood that the two stars have matching proper motions. TGAS astrometry is precise enough that we need to account for the fact that orbital motion may cause slight differences in the proper motions of the two stars. For details of how we account for these differences as well as the exact forms of our two prior probabilities and likelihoods see Andrews *et al.* (2017).

Random alignment catalog. To estimate the rate of contamination in our sample, we adapt the procedure of Lépine & Bongiorno (2007) and generate a catalog of randomly aligned wide binaries by shifting each star by $+2°$ in declination and $+3$ mas yr^{-1} in both μ_α and μ_δ. We then apply our algorithm to identify matches between this shifted star and the original, unshifted catalog. Every resulting pair is a random alignment.

Our wide binary sample. Figure 1 shows the distance and projected separation of candidate pairs in the two catalogs of matched binaries produced using our Bayesian method. The left panel shows those pairs produced due to random alignments while the right panel shows our catalog of genuine binaries. The locus of points in both panels at projected separations of $\sim$1 pc indicates that our sample is dominated by random alignments at these separations. At separations less than $\approx 4 \times 10^4$ AU, our sample is dominated by genuine pairs. By comparing the numbers of pairs with $\theta < 4 \times 10^4$ AU in both panels, we estimate the rate of contamination due to random alignments to be $\approx 5\%$.

3. First Results

Orbital separation distribution. The left panel of Figure 2 shows the orbital separation distribution for pairs within the nearest 100 pc (black) and for pairs at distances between 100 and 200 pc (red). These samples are subject to strong observational biases, but using a more sophisticated analysis in which we account for selection effects, we determine two things: first, the distribution of the sample at relatively larger separations is well characterized by a $P(a) \sim a^{-1.6}$ power law (indicated by the dotted lines). The increase

in the sample of binaries at distances between 100 and 200 pc at $s \sim 10^5$ AU is due to contamination from random alignments. Were this uptick genuine, a corresponding increase would be observed in the sample at distances within 100 pc. Second, the turn-over at $s \sim 3 \times 10^3$ AU is a genuine characteristic of the sample; at smaller separations, the distribution follows one closer to Öpik's law, i.e., $P(a) \sim a^{-1}$. These results are in general agreement with those observed in the wide binary samples of Chanamé *et al.* (2004) and Lépine & Bongiorno (2007).

Radial velocities. Large scale radial velocity surveys such as the Radial Velocity Experiment (RAVE; Kunder *et al.* 2017) provide a useful test of our method; the radial velocities of the components of genuine wide binaries should be consistent. The right panel of Figure 2 shows the radial velocity difference, scaled by the uncertainty in this difference, between the two stars in wide binaries for those pairs in which RAVE radial velocities are available. Horizontal lines bound the region in which the two radial velocities are consistent at the $3\,\sigma$ level. Pairs at projected separations smaller than $4{\times}10^4$ AU (gray vertical line) have a contamination rate of $\approx$5%, and indeed, the stars overwhelmingly have consistent radial velocities. There are a number of pairs (yellow) which have inconsistent radial velocities despite their low contamination fraction. Some of the components of these wide binaries may contain unresolved binaries, and may therefore be hierarchical triple (or higher order) systems.

4. Future Expectations

The second data release from *Gaia* will contain $>10^9$ stars with five astrometrically measured dimensions of phase space. Identifying associated stellar pairs in such a large catalog presents a unique data analysis challenge. Nevertheless, our method is designed for scalability and use with a high performance computing cluster. Using the increase in catalog size as a guide, this data release may contain between 10^5 and 10^6 wide binaries.

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