Fundamental Properties of Co-moving Stars Observed by Gaia

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Abstract

We have estimated fundamental parameters for a sample of co-moving stars observed by Gaia and identified by Oh et al. We matched the Gaia observations to the 2MASS and Wide-Field Infrared Survey Explorer catalogs and fit MIST isochrones to the data, deriving estimates of the mass, radius, [Fe/H], age, distance, and extinction to 9754 stars in the original sample of 10606 stars. We verify these estimates by comparing our new results to previous analyses of nearby stars, examining fiducial cluster properties, and estimating the power-law slope of the local present-day mass function. A comparison to previous studies suggests that our mass estimates are robust, while metallicity and age estimates are increasingly uncertain. We use our calculated masses to examine the properties of binaries in the sample and show that separation of the pairs dominates the observed binding energies and expected lifetimes.

Key words: binaries: general – catalogs – stars: fundamental parameters

Supporting material: machine-readable table

1. Introduction

Stars with similar space motions, also known as co-moving stars, are unique testbeds for stellar and Galactic investigations. They encompass a variety of separations, from ∼1 au, up to the widest separations observed (∼10 pc; Raghavan et al. 2010; Oh et al. 2017b). They can be used as probes of star formation (i.e., Elliott et al. 2016), planetary system survival (Kaib et al. 2013; Kaib & Raymond 2014) and Galactic dynamics (Jiang & Tremaine 2010). Widely separated pairs are of particular utility, as they are sensitive to the mass spectrum of large perturbers in the Milky Way, including giant molecular clouds and black holes (Bahcall et al. 1985; Weinberg et al. 1986, 1987). They are also sensitive to the overall mass distribution, as they are easily disrupted by Galactic tidal forces (e.g., Opik 1976; Hurley et al. 2002; Jiang & Tremaine 2010). When widely separated pairs of stars are found, the individual stellar members serve to form a cluster of stars with N = 2, making them benchmarks for calibrating age and metallicity relations (i.e., Dhital et al. 2012; Rojas-Ayala et al. 2012).

Modern surveys have identified thousands of co-moving binaries within a few kpc of the Sun (Dhital et al. 2010, 2015; Andrews et al. 2017; Oelkers et al. 2017; Oh et al. 2017b). These surveys have identified a new population of stars with separations of <1 to 10 pc (10^2–10^6 au), easily some of the widest pairs known. These pairs were identified using parallaxes and proper motions from Gaia. For the comparison of true three-dimensional (3D) velocity vectors, radial velocities (RVs) are required (Andrews et al. 2017; Price-Whelan et al. 2017). At the largest separations, the false positive rate grows, reaching ∼60%, making RVs critical for identifying true companions (Price-Whelan et al. 2017). With the approach of Gaia data release 2, which includes the RVs of millions of bright stars (G < 12), many more co-moving stars should be discovered.

Despite these advances, the fundamental properties of the widest pairs are not well constrained. First, binary interactions, moving groups, and other phase-space structure can produce stars with similar motions that may not have begun their existence as bound companions, breaking the common assumption of co-eval and co-metallicity. Next, pair-identifying algorithms can fracture larger ensembles of co-moving stars, shedding moving groups into isolated pairs. Algorithms designed to work in observable space (i.e., R.A., decl., proper motion) are more prone to this issue than those working in XYZUVW space. Finally, as the identification is mostly derived from the astrometric properties of the stars, the fundamental properties of the stars themselves, masses, ages, and metallicities, have not been characterized.

In this paper, we explore the fundamental properties (mass, radius, [Fe/H], age, and extinction) of thousands of widely separated pairs. We derive these properties from an ensemble of survey observations, along with isochronal fits to each star. In Section 2, we describe the Gaia observations and the catalog of Oh et al. (2017b), which we use for this analysis. The Oh et al. (2017b) catalog was recently re-organized and re-analyzed by Faherty et al. (2018), which we adopt for this analysis. We supplement the Gaia observations with archival photometry from ground and space-based telescopes. In Section 3, we provide estimates of fundamental parameters for all stars in the catalog, including mass, age, and metallicity. Our estimates are verified by comparisons to prior studies and known fiducial clusters, including the Pleiades and Hyades. In Section 4, we explore our results, including an analysis of the mass properties of the binary systems. Finally, our conclusions are presented in Section 5.

2. Observations

Below, we describe the observations used in our analysis. Our catalog incorporates Gaia photometry and astrometry, as well as photometry obtained during the Two-Micron All-Sky
Survey (2MASS; Skrutskie et al. 2006) and by the Wide-Field Infrared Sky Explorer satellite (WISE; Wright et al. 2010).

2.1. Gaia Observations

The Gaia satellite (Gaia Collaboration et al. 2016a) was launched in 2013 December and will map the entire sky over 5 years, producing the largest and most precise astrometric catalog yet. The final catalog is expected to contain the sky positions, proper motions and distances to ~1 billion unique stars, with a typical parallax, $\varpi$, uncertainty of $\sigma_{\varpi} \sim 20 \mu$as for a Sun-like star with $G = 15$.

The Gaia satellite images the sky using two telescopes separated by a basic angle of 106.5° focusing light onto a focal plane of 106 CCDs (Gaia Collaboration et al. 2016b). The first data release from the Gaia team included proper motions and parallaxes for about 2.0 million nearby bright stars observed by Tycho-2 and Hipparcos. The Tycho-Gaia Astrometric Solution catalog (TGAS; ESA 1997; Høg et al. 2000; van Leeuwen 2007; Michalik et al. 2015; Lindegren et al. 2016) contains mostly bright stars, with 90% of the catalog having $G < 12.05$. The median uncertainty in parallax and position is 0.32 mas, with proper motion uncertainties of 1.32 mas yr$^{-1}$ (Lindegren et al. 2016). Bovy (2017) has shown that the TGAS catalog is mostly complete to a distance of ~200 pc for main-sequence spectral types A through K.

The Oh et al. (2017b) sample of co-moving stars, later examined and re-organized by Faherty et al. (2018), was drawn from the TGAS sample. We summarize the basic sample construction here and refer the reader to Oh et al. (2017b) and Faherty et al. (2018) for details. The Oh et al. (2017b) sample first applied a global signal-to-noise cut on the parallaxes in the TGAS catalog, retaining 619,618 stars with $[S/N]_\varpi > 8$. Next, they searched for stars with similar space motions and 3D separations <10 pc. They identified 271,232 pairs of stars meeting these criteria, then applied a statistical selection based on a fully marginalized likelihood, to identify the most likely pairs. The final Oh et al. (2017b) catalog contained 10606 individual stars organized into 4236 unique groups, with over 319 of those groups containing 3 or more stars (triples or higher order). Faherty et al. (2018) re-analyzed the groups identified by Oh et al. (2017b) using the BANYAN $\Sigma$ code (Gagné et al. 2018; see also Gagné et al. 2017a, 2017b) as well as a literature search and found many of the hierarchical groups were parts of known clusters (i.e., the Pleiades, $\alpha$ Per, and the Hyades clusters) and nearby moving groups and associations (e.g., Lower Centaurus Crux (LCC), Upper Centaurus Lupus).

We used the isochrone python module (Morton 2015) to estimate the fundamental parameters (mass, age, radius, [Fe/H], distance, and extinction) of each star in our sample. The package uses the MESA (Paxton et al. 2011, 2013, 2015) Isochrones and Stellar Track library (MIST; Choi et al. 2016; Dotter 2016) and computes the posterior probability of fundamental parameters given the data. The MIST isochrones span [Fe/H] from $-4.00$ to $-2.00$ in 0.50 dex steps and from $-2.00$ to $+0.50$ in 0.25 dex steps, and $\log_{10}$ $\frac{\Delta M}{\Delta t}$, $\Delta$ from 5.0 to 10.3 in 0.05 dex steps. The isochrones are available in many standard bandpass sets, including Gaia, 2MASS and WISE.\footnote{The isochrones are available at http://waps.cfa.harvard.edu/MIST/}

We computed posterior probabilities on mass, age, radius, [Fe/H], distance, and extinction for the sample conditioned on the measurements of $\varpi$, $G$, $J$, $H$, $K$, and $W1$ and their uncertainties. These posteriors were calculated using the trilinear interpolation schemes within isochrones and assumed priors described in Morton (2015), including a distance prior from the parallax reported by Gaia and a [Fe/H] prior from metallicity estimates (Bovy 2016) of nearby stars by Casagrande et al. (2011). The extinction prior for each star was bounded at its maximum value with an extinction estimate calculated from the reddening reported in the Schlegel
Figure 1. Upper panel: a corner plot (Foreman-Mackey 2016) of posterior samples derived from our analysis for one example star, TYC 9456-1172-1. The various panels are two-dimensional projections along different axes of samples, along with histograms of the samples in $G$, $J$, $H$, $K$, and $W_1$. The observed values are over-plotted as blue vertical lines. Lower panel: a corner plot of the estimated fundamental parameters: mass, radius, [Fe/H], age, distance, and $A_V$ for the star.
et al. (1998), using the re-calibrated values (Schlafly & Finkbeiner 2011) and the Fitzpatrick (1999) reddening law. Next, the posterior distributions were sampled using the MCMC ensemble sampler emcee (Foreman-Mackey et al. 2013). We initialized 500 walkers with a random initialization bounded by values described by Morton (2015) and allowed them to explore the posterior probabilities for 100 iterations. The sampler was then re-initialized as at the location with the highest likelihood, with a small Gaussian perturbation in all dimensions. The walkers then ran for 700 steps, with a burn-in of 200 steps, and the last 500 steps were recorded. The fundamental parameters listed were obtained by taking the median posterior samples, along with the 15% and 85% percentile samples. We compared the posterior samples of each parameter to their priors and observed differences, indicating the supplemental photometry aided in constraining the model parameters. An example of our posterior samples is shown in Figure 1. For 241 stars, the sampler was unable to converge upon a solution. Therefore we report fundamental parameters for 9754 of our input sample. All resultant fundamental parameters (mass, age, radius, [Fe/H], distance, and extinction) are listed in Table 1 and summarized in  Figure 2.

4. Discussion

In the following section, we discuss the results of our analysis. We begin with a validation of our analysis, by comparing our photometrically derived physical parameters to previous studies of the same stars. This is followed by an analysis of members (bona fide and suspected) of the nearby clusters. We also present color–magnitude (CMDs) diagrams with regard to fundamental parameters. Next, we examine the distributions of masses, compositions, and ages recovered by our analysis. Finally, we discuss the mass ratio and binding energy distributions.

4.1. Validation

4.1.1. Comparison to Geneva-Copenhagen Survey (GCS) Members

We compare our photometrically derived fundamental parameters to the catalog of Casagrande et al. (2011), who re-analyzed the GCS of 16682 FGK dwarfs with Stromgren photometry. Their work re-calibrated the temperature scale, and resulted in mass, age, and metallicity estimates of the GCS sample. The catalogs were matched on Hipparcos catalog number. This yielded 672 matches between our sample and the Casagrande et al. (2011) catalog. In Figure 3, we compare our fundamental parameter results to those from GCS for the stars in common between the two. Overall, the agreement in mass between the two catalogs is good. The same agreement is not seen with age and metallicity, indicating that these parameters may be less certain. We calculated the median and 15th and 85th percentiles of the differences between the two surveys (in the sense of GCS—this study). They are $-0.03 \pm 0.08 \, M_\odot$ for mass (using the Padova isochrones), $0.13^{+1.73}_{-2.03} \times 10^9$ year for age, and $-0.05^{+0.19}_{-0.19}$ dex
for metallicity. In each case, the median difference between the two samples is consistent with zero.

4.1.2. Comparing to Nearby Cluster and Moving Group Members

Next, we compared the derived fundamental properties to known clusters from Oh et al. (2017b) as identified in the re-organized catalog of Faherty et al. (2018). The groups with the largest number of members were the Pleiades (Cummings 1921; Stauffer et al. 1989), α Per (Crawford & Barnes 1974), and the Hyades open clusters (Perryman et al. 1998), and the LCC group (Blauw 1946; de Zeeuw et al. 1999). In Figure 4, we show the derived fundamental parameters for the cluster members. The metallicity distributions for the four associations are quite similar, containing mostly solar metallicity stars, in agreement with most spectroscopic results. We over-plot literature estimates of the cluster metallicities as vertical lines. These are −0.01 for the Pleiades, 0.15 for the Hyades, 0.14 for α Per, and 0.0 for the LCC (Netopil et al. 2016; Cummings et al. 2017). The age distribution is shown in the upper right, along with literature estimates of the age of each group. The ages assumed are 130 Myr for the Pleiades (Barrado Navascués et al. 2004), 85 Myr for α Per (Barrado Navascués et al. 2004), 625 Myr for the Hyades (Perryman et al. 1998), and 17 Myr for the LCC moving group (Mamajek et al. 2002; Pecaut et al. 2012).

Those values are over-plotted as vertical lines in the figure. Overall, the agreement between our derived values and literature estimates (often derived spectroscopically) is marginal, but the enhancement of Myr stars found in LCC indicates that some age discrimination is possible with isochrone fitting. In the lower left panel, we compare the derived distance estimates (based on the isochronal fitting with a prior derived from Gaia observations) to literature estimates of the mean distance for each cluster. Due to the exquisite precision and accuracy of the Gaia data, the agreement between our derived values and the literature values are good. The adopted average distances for the Pleiades (Mädler et al. 2016), α Per (van Leeuwen 2009), Hyades (van Leeuwen 2007), and LCC (de Zeeuw et al. 1999) are 135 pc, 172 pc, 47 pc, and 118 pc, respectively. In lower right panel, we show the mass distributions of the four groups, which all share a similar slope. The Pleiades and Hyades demonstrate a larger number of observed low-mass stars, with α Per containing a larger fraction of high mass stars. However, as these are not complete surveys of the clusters, no strong statements can be made on intrinsic differences in the mass distributions. Overall, we find good agreement between our analysis and literature values for the metallicity and distance estimates, with less agreement between age estimates. This reflects the larger scatter seen in the

![Figure 2. Corner plot of fundamental parameter for our entire sample. Most stars in our sample are solar metallicity, with estimated ages of ∼10^9 years. There are no obvious correlations between mass and metallicity or age, which suggests that our mass estimates are robust.](image-url)
age agreement in Section 4.1.1 and the challenges in estimating ages from photometry.

In Figure 5, we plot the Gaia-2MASS CMD of our total sample, along with members of the four clusters. The $G-K$ colors and $K$ magnitudes have not been corrected for extinction in any of the CMDS presented in this analysis. The Pleiades, $\alpha$ Per, and Hyades members occupy similar areas of color–magnitude space, due to their similar ages and compositions. The LCC members demonstrate significant scatter. This is likely due to the youth of the cluster, and the larger spread in distance, as seen in Figure 4. For each cluster, stars are found above the main sequence. For the older clusters, these are likely unresolved binaries, which are more common in wide binaries (Law et al. 2010), forming hierarchical multiple systems. Note that the stars identified as cluster members are not necessarily wide binaries.

4.1.3. Present-day Mass Function (PDMF)

We further scrutinized our mass estimates by determining the PDMF. The distribution of all masses can be found in Figure 2. For our PDMF measurement, we selected stars with masses $>1M\odot$ within 200 pc, as TGAS is complete within 200 pc Bovy (2017) at these masses. The histogram of mass estimates for stars within 200 pc are shown in Figure 6. Bin sizes were chosen using Knuth’s rule (Knuth 2006) as implemented in astroML (Vanderplas et al. 2012; Ivezic et al. 2014; VanderPlas et al. 2014). Solar-mass stars are the most common member of our sample, with low-mass stars ($0.2-1.0 M\odot$) as the next most common constituent. The PDMF includes information on both the initial mass function (Bochanski et al. 2010) and the star formation rate. In Figure 7, we plot the number of stars per mass bin, in log–log scale, for stars with $1.0 < M/M\odot < 5.0$ along with estimates of the posterior probability of a power-law fit. The slope of the power-law, commonly given as $\alpha$, where $\alpha = -2.35$ is the slope measured by Salpeter (1955), was $\alpha = -4.55 \pm 0.05$, estimated by samples of the 16th, 50th, and 85th percentiles. While our sample is not complete, it is well matched to the estimates of the PDMF for $M > 1M\odot$ by Reid et al. (2002), $\alpha = -5.2 \pm 0.4$ and the recently derived PDMF from Bovy (2017) $\alpha = -4.7$, which used a different set of isochrones to estimate masses of TGAS stars.

4.2. Color–Magnitude Diagrams

In Figures 8 and 9, we plot $M_K$ versus $G-K$ CMDs of our binary and total samples, respectively. In Figure 8, we highlight the $N = 2$ pairs, with a line connecting each component, after Price-Whelan et al. (2017). The majority of the stars are found
in pairs of main-sequence stars, with a smaller subset containing a main-sequence star with a red giant branch stars.

4.3. Binary Properties

We examined the properties of binaries in our sample. Co-moving binaries (with \( N = 2 \)) are usually assumed to be co-eval members with similar compositions, but recent results have shown that pairs may not always have the same metallicity (i.e., Oh et al. 2017a). Below, we examine the differences in metallicity and age for pairs, and identify sets of “twin” stars in the sample. We also highlight the properties of the 10 most widely separated pairs. Finally, because our mass estimates are the most robust property measured, we examine the mass properties of the binaries, including their mass ratio and binding energy distributions, along with their expected dissipative lifetimes.

4.3.1. Metallicity and Age Distributions

As shown in Section 4.1, metallicity and age have significant uncertainties when estimated using photometry alone. In Figure 10, we examine the difference in [Fe/H] and log age (year) for the sample. In general, the agreement in metallicity between members of binaries is good, with a broad peak centered on \( \Delta_{[\text{Fe/H}]} = 0 \) and most stars agreeing within \( \sim 0.2 \) dex, on order with our external accuracy as determined in Section 4.1.1. Our large uncertainties with respect to age are evident in Figure 10, with some Myr stars being matched to Gyr counterparts. This is likely due to pairs containing members along the giant branch and main sequence. In Figure 9, many of the youngest stars can be found along the RGB, which suggests those ages are not trustworthy. These stars are being assigned ages appropriate for pre-main-sequence (PMS) stars, which also affects their isochronal distance estimates, as RGB and PMS stars have much different luminosities. We confirmed this by comparing the parallactic and isochronal distances, and many RGB stars with erroneous young ages have large differences (>50 pc) in their distance estimates.

We also examined the differences in age and metallicity as a function of the separation of the individual stars. In Figure 11, we show the differences as a function of separation, as well as the mean and standard deviation among 50 bins. There are no clear correlations with physical separation, which suggests that
the pairs with large separations may be bona fide binaries. We also examined the distributions in age and metallicity differences in randomly associated pairs from our binary sample. For both age and metallicity, the standard deviation of differences was larger for the randomly associated stars as compared to our original sample.

Despite the uncertainties in [Fe/H] and age, we searched for binaries with identical members in terms of mass, age, and composition. To select these twins, we enforced that the median estimates for both stars needed to match within 0.015 in mass, [Fe/H], and log age. Three pairs of twins were identified and are summarized in Table 2.

Finally, we examined the 10 pairs with the largest physical and projected separations. Their properties are summarized in Tables 3 and 4. The pairs in Table 3 are presented in order of increasing separation, but they all have separations \(~10\) pc, while the projected distances vary. As discussed in Oh et al. (2017b), the co-moving stars separated by the largest distances are most prone to false positives. Fundamental property estimates can test this, as false positives are unlikely to have the same metallicity and age. For the small sample in Table 3, that is not an issue, as many have metallicity estimates that agree within their uncertainties. Given the difficulty in photometrically estimating ages, co-evality as determined by isochrone fitting cannot reliably rule out false positives. We also note that at least two pairs in Table 3 are main-sequence stars paired with a red giant star.

4.3.2. Binary Mass Properties

For each binary system, we calculated the separation (in pc and au), the mass ratio, defined as the mass of the secondary divided by the mass of the primary star, the gravitational binding energy, and the dissipative lifetime. The binding
energy was calculated using:

\[ U = \frac{G M_1 M_2}{R} \]  

where \( G \) is the universal gravitational constant, \( M_1 \) and \( M_2 \) are the masses of the stars and \( R \) is the physical separation between the two components. The dissipative lifetime of the binaries was estimated using:

\[ \tau = \frac{1.212 \times (M_1 + M_2)}{R} \]

with \( \tau \) in Gyr, \( M_1 \) and \( M_2 \) in solar masses and \( R \) in pc, from Dhital et al. (2010).

In Figure 12, we show the summary corner plot of the mass properties of pairs in our sample. Some trends are evident. First, the mass ratio distribution rises toward values of unity.
The binding energy and lifetimes trend together, with the most tightly bound binaries having the largest lifetimes. The separation between components has the largest influence on binding energy and lifetime, as it varies to a larger extent than the masses of the binary components. This is also evident in Figure 13 which compares the binding energy to the separation between binary components and the total mass of the binary. The median uncertainty in binding energy for the sample is $\sim 20\%$, with the uncertainty in the physical separation of the binary components being the largest factor. Considering that the uncertainty in separation is dominated by the relative uncertainty in parallax, these uncertainties are small, due to the exquisite precision of Gaia. Tightly bound components, with large binding energies and long lifetimes, are only found at small separations. This trend is also evident when the projected separation of the system is considered, as shown in Figure 14. The projected separations do not track the binding energy as directly as the 3D separation, by definition, but there is a trend toward the closest stars (on the sky) also having large binding energies. On the other hand, the total mass of the most tightly bound systems is not necessarily large, with many having total masses less than two solar masses. We see that many stars in the sample have relatively low binding energies (and large separations) as noted in Oh et al. (2017b) and Oelkers et al. (2017). These stars are likely formerly bound systems with similar space motions.

In Figure 15, we plot the overall mass ratio distribution, defined as the mass of the secondary divided by the mass of the primary component of each binary. Overall, the mass ratio distribution grows as the ratio gets closer to unity. In the lower panel, we divide the distribution in terms of the masses of the primary. A clear trend toward flatter distributions arises as the mass of the primary increases. This is partly due to the definition, as the lowest mass primary stars can only have companions that are relatively equal in terms of mass, while as the primary’s mass increases, those stars can be paired with secondaries of a variety of masses.

Figure 8. The color–magnitude ($M_K$ vs. $G-K$) for pairs in our sample, after Price-Whelan et al. (2017). Each binary is connected by a colored line. Most of the sample is composed of main sequence + main sequence pairs, but some main sequence + red giant branch stars are observed.
5. Conclusions

We analyzed a sample of 9995 co-moving stars identified in Gaia-TGAS by Oh et al. (2017b) and re-organized by Faherty et al. (2018). Our analysis used isochrone fitting incorporating $G$, $J$, $H$, $K$, and $W1$ observed photometry. Our results demonstrated robust estimates of stellar masses, as verified by comparisons to other analyses of the same stars, cluster properties, and computation of the PDMF. We report fundamental parameters for all stars in the sample and examined the binary properties of pairs in the system. Many pairs in the catalog are weakly bound, sharing binding energies comparable to Neptune and the Sun (Dhital et al. 2010). The
The dominant property of a pair’s binding energy and lifetime is its physical separation. This catalog, derived from the exquisite astrometry of Gaia, has revealed a large population of loosely bound systems, which will be ideal for large spectroscopic follow up (i.e., Price-Whelan et al. 2017). Future samples of co-moving stars in Gaia will likely be dominated by loosely bound systems, making spectroscopic observations critically important. Spectra readily reveals the radial velocity of a star, allowing for the direct comparison of a star’s 3D velocity vector to any companion. Furthermore, spectra can be used to precisely estimate stellar chemical composition, which is uncertain with photometric techniques. However, to address the significant age uncertainties, other techniques, like gyrochronology (Douglas et al. 2014, i.e.,) or astroseismology (Chaplin et al. 2014) are likely required.

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### Table 2

#### Stellar Twins

| TGAS Source ID | R.A. (degree) | Decl. (degree) | Mass (M\(_\odot\)) | Radius (R\(_\odot\)) | [Fe/H] (dex) | log(age) (year) | Distance (pc) | A (mag) | Sep (pc) |
|----------------|---------------|----------------|---------------------|---------------------|--------------|----------------|--------------|---------|---------|
| 315280928867786992 | 106.1067 | 5.6167 | 1.30±0.05 | 1.46±0.03 | 0.03±0.01 | 9.28±0.11 | 140.3±1.1 | 0.09±0.00 | 8.6 |
| 312640559378754560 | 104.8429 | 4.1459 | 1.29±0.05 | 1.42±0.04 | 0.04±0.01 | 9.27±0.10 | 130.9±1.2 | 0.16±0.00 | 8.6 |

### Table 3

#### Pairs with Largest Physical Separations

| TGAS Source ID | R.A. (degree) | Decl. (degree) | Mass (M\(_\odot\)) | Radius (R\(_\odot\)) | [Fe/H] (dex) | log(age) (year) | Distance (pc) | A (mag) | Sep (pc) |
|----------------|---------------|----------------|---------------------|---------------------|--------------|----------------|--------------|---------|---------|
| 1620697834607327056 | 222.4335 | 64.2362 | 0.89±0.01 | 0.91±0.01 | 0.10±0.00 | 10.12±0.02 | 216.5±12.3 | 0.01±0.00 | 9.99 |
| 166817737591697536 | 216.1852 | 64.6168 | 1.13±0.04 | 1.25±0.01 | 0.01±0.00 | 9.53±0.15 | 203.3±4.6 | 0.01±0.00 | 9.99 |

### Table 4

#### Pairs with Largest Projected Separations

| TGAS Source ID | R.A. (degree) | Decl. (degree) | Mass (M\(_\odot\)) | Radius (R\(_\odot\)) | [Fe/H] (dex) | log(age) (year) | Distance (pc) | A (mag) | Proj. Sep. (pc) |
|----------------|---------------|----------------|---------------------|---------------------|--------------|----------------|--------------|---------|----------------|
| 115120513259639040 | 135.6178 | 86.6559 | 0.91±0.02 | 0.86±0.00 | 0.02±0.00 | 9.59±0.12 | 50.0±0.7 | 0.05±0.00 | 10.96 |
| 5529637314836040 | 75.2248 | 77.7755 | 0.99±0.02 | 1.27±0.04 | -0.16±0.08 | 9.87±0.02 | 50.8±0.6 | 0.05±0.00 | 10.96 |

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### Table 4
(Continued)

| TGAS Source ID | R.A. (degree) | Decl. (degree) | Mass ($M_\odot$) | Radius ($R_\odot$) | [Fe/H] (dex) | log (age (year)) | Distance (pc)$^a$ | $A_v$ (mag) | Proj Sep. (degree) |
|----------------|---------------|----------------|-------------------|-------------------|-------------|------------------|------------------|------------|------------------|
| 13277192518505665656 | 248.2193 | 35.0751 | $0.9^{+0.02}_{-0.01}$ | $0.87^{+0.02}_{-0.01}$ | $0.09^{+0.07}_{-0.04}$ | $9.74^{+0.16}_{-0.10}$ | $34.7^{+0.13}_{-0.4}$ | $0.01^{+0.00}_{-0.00}$ | 12.55 |
| 138963921242104704 | 234.0527 | 40.8321 | $0.60^{+0.01}_{-0.01}$ | $0.58^{+0.01}_{-0.01}$ | $-0.12^{+0.06}_{-0.06}$ | $9.79^{+0.25}_{-0.26}$ | $38.2^{+0.16}_{-0.16}$ | $0.01^{+0.00}_{-0.00}$ | 12.55 |
| 4753362798950483072 | 40.5351 | $-46.5248$ | $1.45^{+0.00}_{-0.00}$ | $2.48^{+0.18}_{-0.18}$ | $0.07^{+0.07}_{-0.07}$ | $9.43^{+0.02}_{-0.02}$ | $42.4^{+0.18}_{-0.7}$ | $0.01^{+0.00}_{-0.00}$ | 13.17 |
| 4960514947152086016 | 24.5134 | $-40.2936$ | $0.67^{+0.01}_{-0.01}$ | $0.63^{+0.01}_{-0.01}$ | $0.11^{+0.05}_{-0.05}$ | $9.34^{+0.29}_{-0.29}$ | $38.9^{+0.15}_{-0.5}$ | $0.01^{+0.00}_{-0.00}$ | 13.17 |

Note. $^a$ Distances are estimated from isochronal fits.

Figure 12. A corner plot summary of the mass properties of binaries in our study. We show the mass ratio, primary and secondary masses in solar masses, binding energy in ergs (log scale), binary lifetime in Gyr (log scale), physical separation in au (log scale), and projected separation in arcseconds (log scale). The most tightly bound, and longest lived systems are found close to each other.
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Figure 14. Binding energy vs. total mass, shaded by projected separation (log scale, in arcseconds). While the trends seen in Figure 13 are not as apparent, the pairs with the largest binding energies are also found at the smallest projected separations.

Figure 15. Upper panel: mass ratio histogram for stars in our sample. Lower panel: mass ratio distribution for various bins in primary mass. As the mass of the primary increases, the mass ratio distribution moves away from unity to increasingly flatter distributions, indicating that the secondary masses are drawn from the same distribution as the primary.

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Software: Numpy (van der Walt et al. 2011), jupyter (Th omas et al. 2016), scipy (Jones et al. 2001), isochrones (Morton 2015), astroML (Vanderplas et al. 2012; Ivezić et al. 2014; VanderPlas et al. 2014), emcee (Foreman-Mackey et al. 2013), corner (Foreman-Mackey 2016), BANYAN (Gagné et al. 2014, 2018), Matplotlib (Hunter 2007), Topcat (Taylor 2005).

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