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A Report on Stellar Companion Mass Estimates Within Our Solar Neighborhood

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ABSTRACT

We present mass estimates and companion demographics on stellar multiples within 25 pc, using a survey of stars of all spectral types done by Robo-AO and supplemented by Gaia. The survey combined direct imaging by Robo-AO, a robotic adaptive optics instrument for 2-m class telescopes, to detect tight companions ($< 4''$ separation) and with Gaia astrometry to detect wider co-moving companions. We estimated the masses for 267 companions using empirical relations and, for a subset of 97, dynamical mass estimates. We utilized previous mass-magnitude models using contrasts measured from Gaia and Robo-AO to estimate the mass and also used the orvara python package, a Markov-Chain Monte Carlo (MCMC) orbit fitter using the companion astrometry and Hipparcos-Gaia proper motion accelerations, to estimate dynamical masses. We compare agreements and discrepancies in mass estimates from these two methods.

Keywords: binaries: close – instrumentation: adaptive optics – techniques: high angular resolution – methods: data analysis – methods: observational

1. INTRODUCTION

Studying the orbital dynamics in stellar multiples allows us to calculate properties of the individual stars, such as their masses, which **are** fundamentally linked to a star's formation, composition, and evolution sequence. The Hipparcos-Gaia Catalog of Accelerations (HGCA; Brandt 2018) is a list of stars with accelerations calculated from the change in proper motions measured by the Gaia spacecraft and Hipparcos satellite. An orbiting companion causes an acceleration on the primary star, the strength of which correlates with the companion's mass and separation. However, a massive more widely separated companion, could cause the same acceleration signal on the primary star as a smaller, closer-in companion, leading to a mass-separation degeneracy. Direct imaging confirms the presence of a companion and helps break the mass-separation degeneracy by measuring the on-sky separation.

We used the result from the Robo-AO Solar Neighborhood Survey (Salama et al. 2022) which utilizes Robo-AO (Baranec et al. 2014), a robotic adaptive optics instrument used for a volume-limited survey which directly imaged over 1200 stars within 25 pc and detected 299 stellar multiples. The survey is also supplemented with Gaia data to confirm physical association and to search for companions wider than $4''$. We calculated the masses for the companions in two ways: using empirical photometry-mass relations and orbital fits to astrometry data, when available. These two methods of calculating masses led us to estimate masses for 267 companions, 118 of which are at separations within $< 4''$.

2. COMPANION MASS CALCULATIONS

We used empirical photometry-mass relations and orbit fits to estimate masses from the Salama et al. (2022) survey. For the former we interpolated the color-Teff grids from Pecaut & Mamajek (2013) and Kraus & Hillenbrand (2007) which reported empirical relations between masses and stellar magnitudes. For the latter we used `orvara` (Brandt et al. 2021), a python package which fits orbits utilizing the Markov Chain Monte Carlo method, using accelerations from HGCA, their epochs, and relative astrometry from Robo-AO and/or Gaia companion detections.

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2.1. *Mass estimates from photometry data*

We used empirical relations from Pecaut & Mamajek (2013) and Kraus & Hillenbrand (2007) relating stellar magnitudes to stellar masses and temperatures, to estimate masses from photometry. Using Gaia parallaxes, we converted our apparent magnitudes to absolute magnitudes and then estimated the masses of our companions by interpolating across the absolute magnitude-mass relations. Mass estimates for Robo-AO detected companions measured in the i-band were done using relations from Kraus & Hillenbrand (2007). For companions resolved by Gaia, we estimated their masses using their absolute G magnitudes and Gaia colors (Bp-Rp and G-Rp). Thirty companions had mass estimates from all four magnitudes and colors, 153 companion masses were estimated from the Gaia filters, and 41 companions had only estimates from i'-band magnitudes. The final reported empirical mass estimate is the average mass across filters.

We propagated the magnitude uncertainties, reported by Gaia and Robo-AO, and the distance uncertainties, reported by Gaia parallaxes, to calculate our mass estimate uncertainties. We do not have empirical mass estimates for 46 companions as there was insufficient photometry information. However, for 14 of those, we have dynamical mass estimates from HGCA and relative astrometry data.

2.2. *Dynamical mass estimates from astrometry*

The HGCA reports accelerations between the Hipparcos and Gaia proper motion measurements of the primary stars where one of the likely causes of this acceleration is the presence of an orbiting companion (Brandt 2021). In the Salama et al. (2022) survey the HGCA was used to analyze trends between the acceleration of the primary star and the presence of a companion. In this work we used `orvara`, a python package developed by Brandt et al. (2021), to estimate the individual component masses of our stellar binaries. `orvara` fits Keplerian orbits to data from radial velocity, relative astrometry, and/or accelerations from HGCA. We use `orvara` to fit orbits from our survey to have a more comprehensive mass analysis for the secondary companions.

We utilized HGCA accelerations and relative astrometry from Robo-AO and Gaia as inputs for `orvara`. The primary mass estimates and their associated errors from the mass-luminosity relations were given to `orvara` as initial parameters. Then we ran orbit fits for systems with significant measured accelerations, defined as having a $\chi^2 > 11.8$. There were 187 primary stars with acceleration measurements in the HGCA, 97 of which met the χ^2 threshold and were thus eligible for the dynamical mass estimates.

Using `orvara`, we measured masses for 97 companions, 35 of which had separation and position values from both Gaia and Robo-AO. This constrained the orbit more by giving `orvara` two relative astrometry positions rather than one. We then retrieved the resulting MCMC best fit for the primary and companion masses.

2.3. *Discussion*

There is a greater distribution of companion masses from `orvara` compared to the empirical method. Figure 1b compares the masses between the empirical and `orvara` methods, where `orvara` tended to converge to lower mass estimates compared to the empirical mass estimates for the companions. Figure 1c shows the discrepancies between the dynamical and empirical estimates which could be due to only having 1-2 epochs when using `orvara`, which does not allow for a well-constrained orbit. It is expected that the primary mass estimates from `orvara` and the empirical method are similar, as seen in Figure 1a, since we used primary mass estimates as priors for `orvara`. However, it is still worthwhile to note these masses since it gives a sense of the mass range.

3. CONCLUSION

We estimated masses for 267 companions detected by the Robo-AO survey of 1200 stars within 25pc. Using empirical mass relations derived from Kraus & Hillenbrand (2007) and Pecaut & Mamajek (2013), we estimated masses using available photometry in the G-band, Bp-Rp, G-Rp colors, and/or i-band. We then used `orvara`, an orbit-fitting tool which uses HGCA accelerations and relative astrometry points from Robo-AO and/or Gaia, to estimate dynamical masses for 97 companions. We selected multiples whose primary star had a $\chi^2 > 11.8$. The `orvara` fits is not well constrained due to the limited number of epochs used. In order to get better constrained dynamical mass

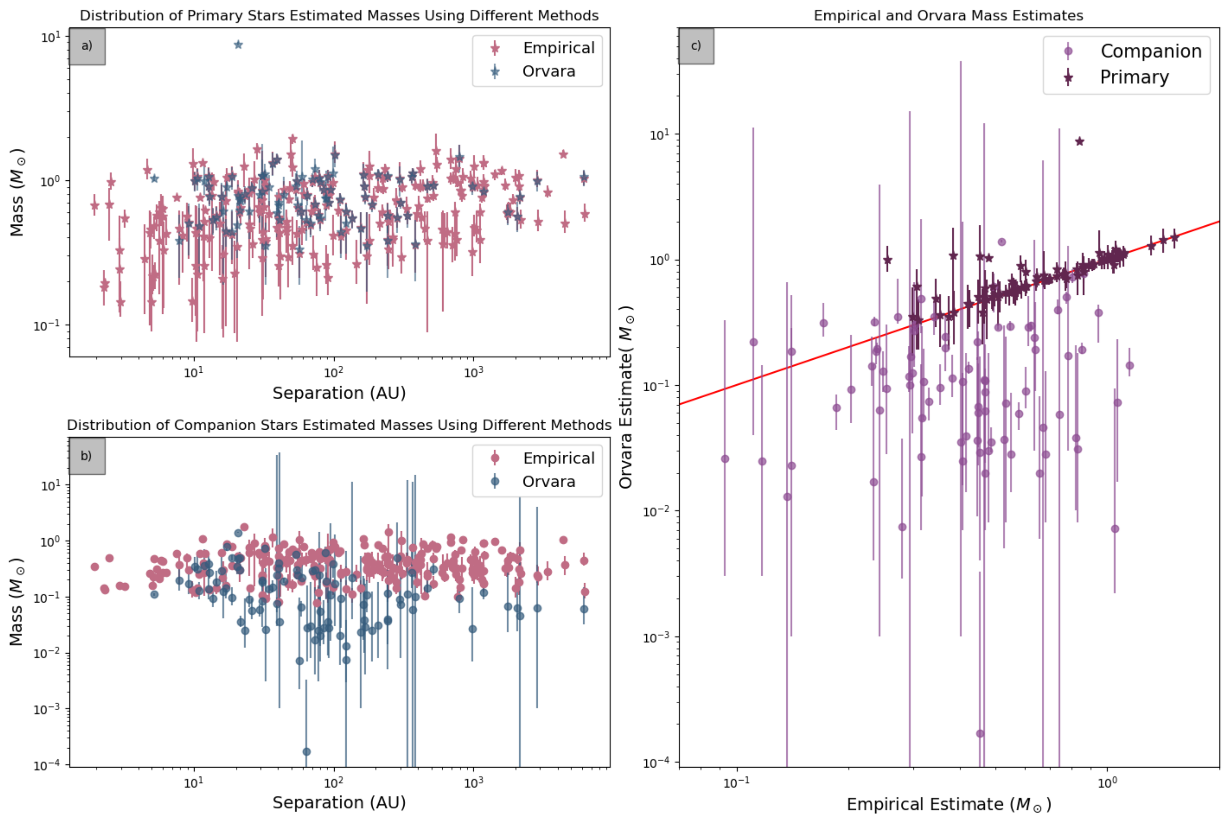

Figure 1: Distribution of estimated masses from the empirical and orvara methods. Plots a and b show the primary and companion masses, respectively, as a function of the companion's projected separation. Plot c compares the different methods of estimating individual component masses. **Data behind this figure(Gaia IDs, separations, and mass estimates) are available in the electronic version.**

estimates for these systems using orbital fitting methods, more observations will be needed to track the orbit over time.

This research has made use of the SIMBAD database, operated by Centre des Données Stellaires (Strasbourg, France), and bibliographic references from the Astrophysics Data System maintained by SAO/NASA.

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Facilities: PO:1.5m (Robo-AO)

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