The orbital eccentricities of Directly Imaged Companions using Observable-Based Priors: Implications for Population Distributions

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Introduction

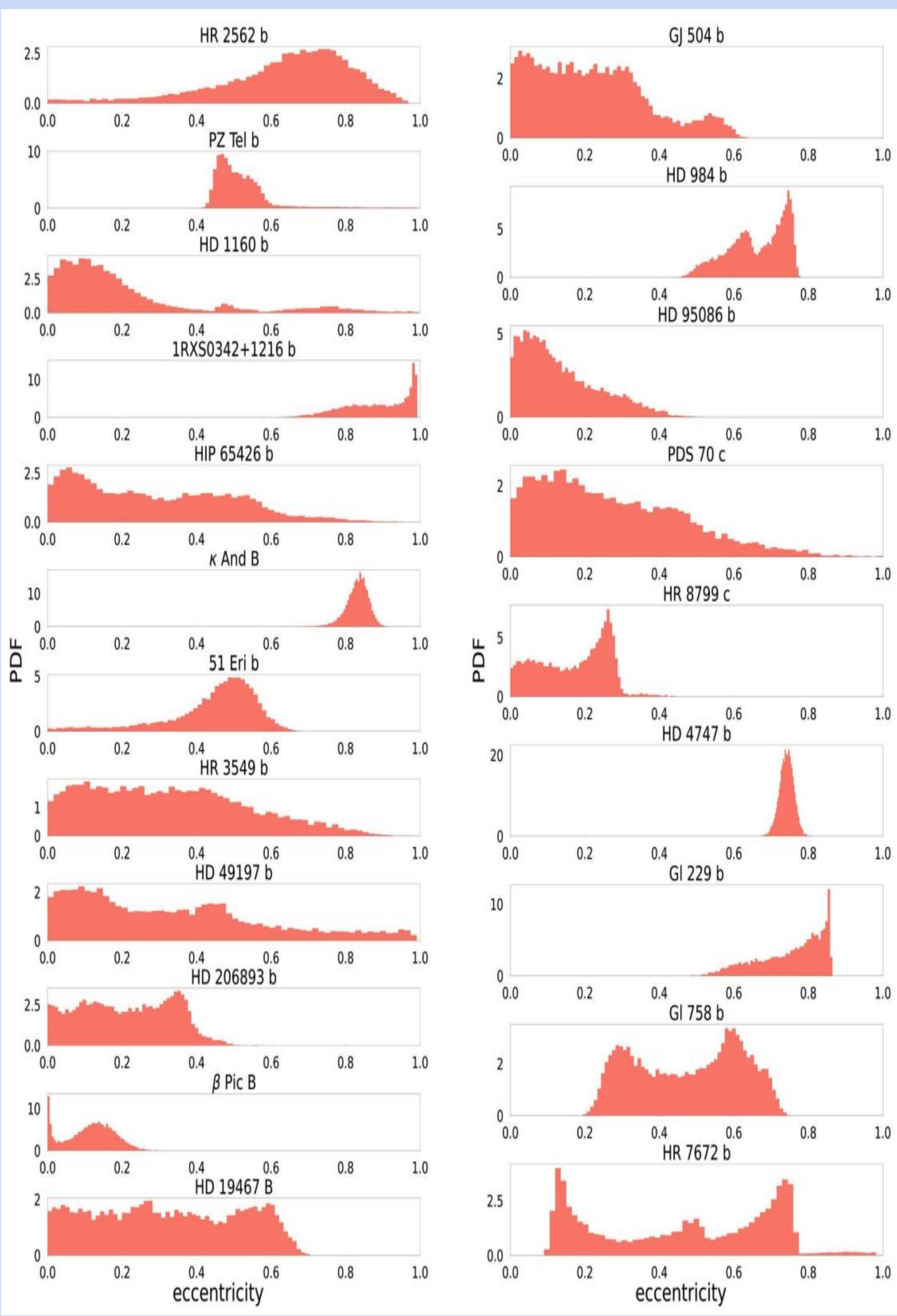
The eccentricity of a substellar companion is an important tracer of its formation history. Directly imaged companions often present poorly constrained eccentricities. Within the Bayesian framework, prior probability distributions (priors) for each orbit parameter must be assumed to ultimately infer posterior probability distributions (posteriors) for each parameter. The most common priors assumed for orbital parameters are model-based priors (i.e., priors on the 6 Keplerian orbital elements). Uniform priors have been shown to have biases, including a tendency towards artificially high eccentricities. Observable-based priors improve the high eccentricity bias presented by uniform priors' orbit fitting. **The goal of this work is to analyze how this change in priors for orbit fitting impacts the eccentricity distribution of directly imaged companions at a population level and to determine the amount of astrometric coverage required for meaningful orbital parameter posteriors**

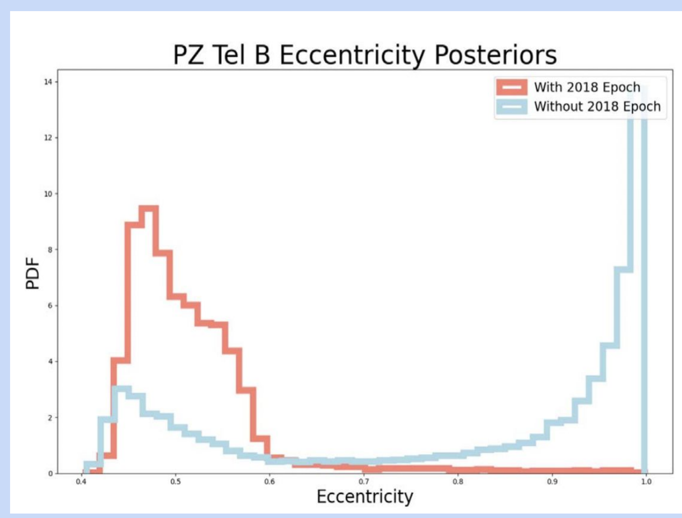
Methods

- We fit for the orbits of **21 companions** with updated astrometry and radial velocities (RVs) when available
- Use a Beta distribution to parametrize the eccentricity distribution of the entire population
  - Compare eccentricity distribution to the ones obtained by previous works, such as Bowler et al 2020 (N = 27 directly imaged companions) and Kipping 2013 (N = 396 short period exoplanets from radial velocities)
  - Separate the population by mass to search for possible distinctions between gas giants ($M < 15\ M_J$) and brown dwarfs ($15\ M_J < M < 75\ M_J$)
- Simulate how much orbital coverage is required for meaningful orbital posteriors under the assumptions made for direct imaging

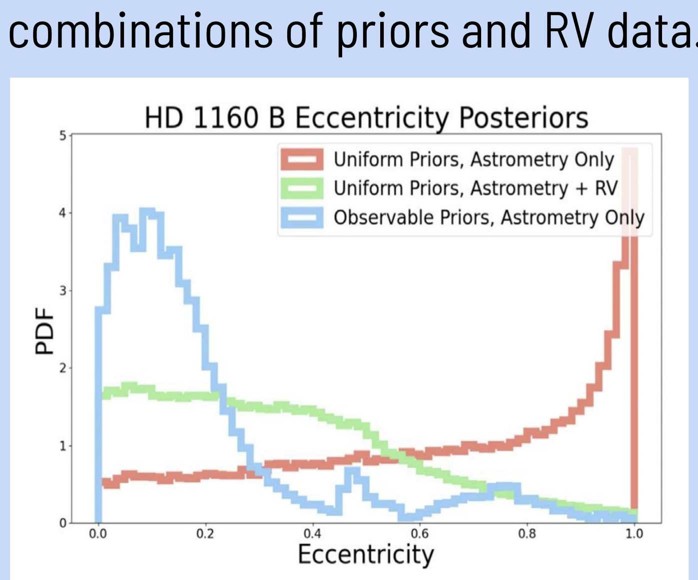
Results

Individual Orbit Fits

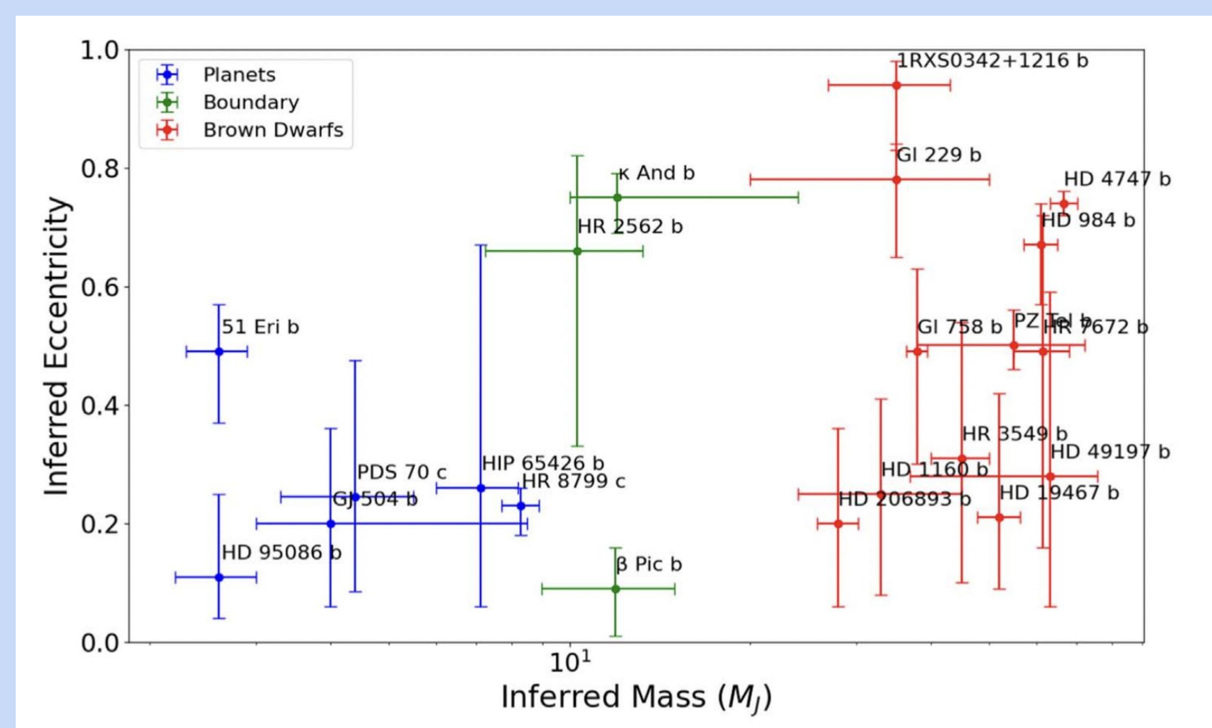




Top: PZ Tel B eccentricity posteriors with and without a new astrometry epoch from 2018. **Left:** eccentricity posteriors with observable-based priors for the 21 companions in the sample. **Bottom:** HD 1160 b eccentricity posteriors with different combinations of priors and RV data.



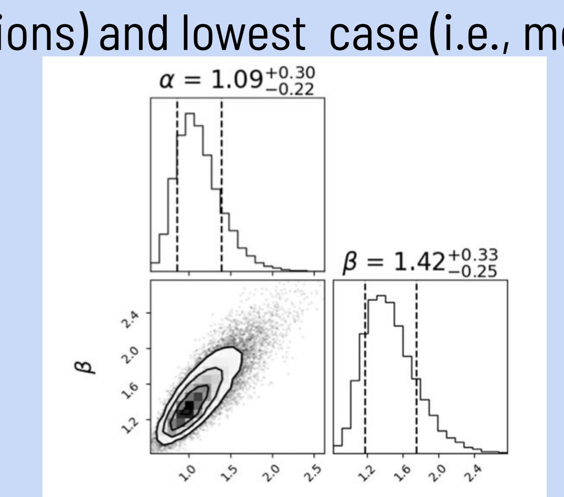
Parent Eccentricity Distribution

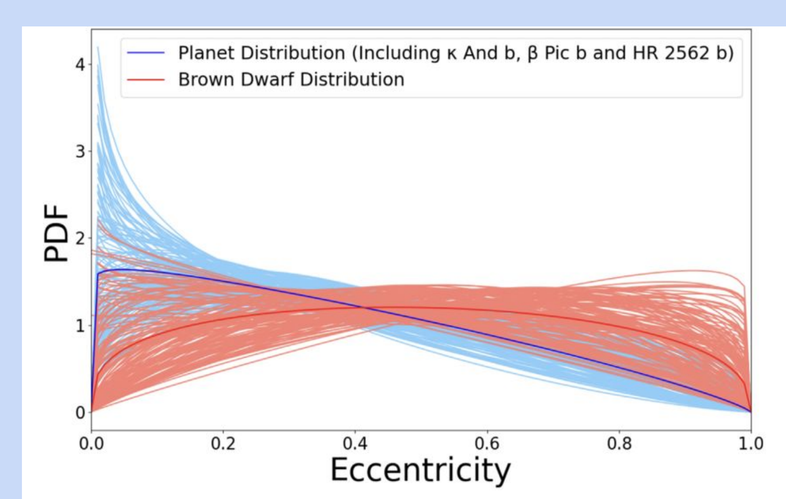


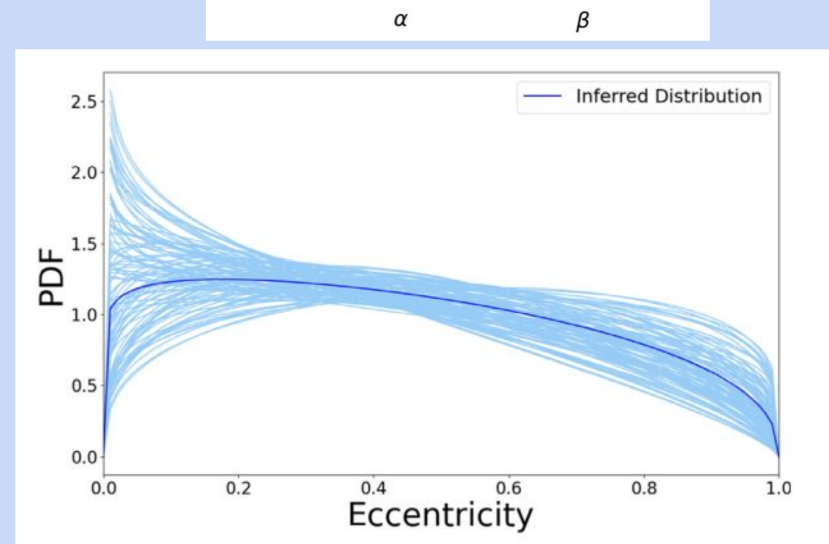
Top: 68th percentile of mass vs . eccentricity for the objects in the sample. Mass estimates are from the literature, while eccentricity estimates are from this work. Blue dots represent "planets," or objects under 15 M_J, while red dots represent "brown dwarfs," or objects with masses above 15 M_J Green dots are "boundary" objects: intermediate-mass objects that could be in either distribution.

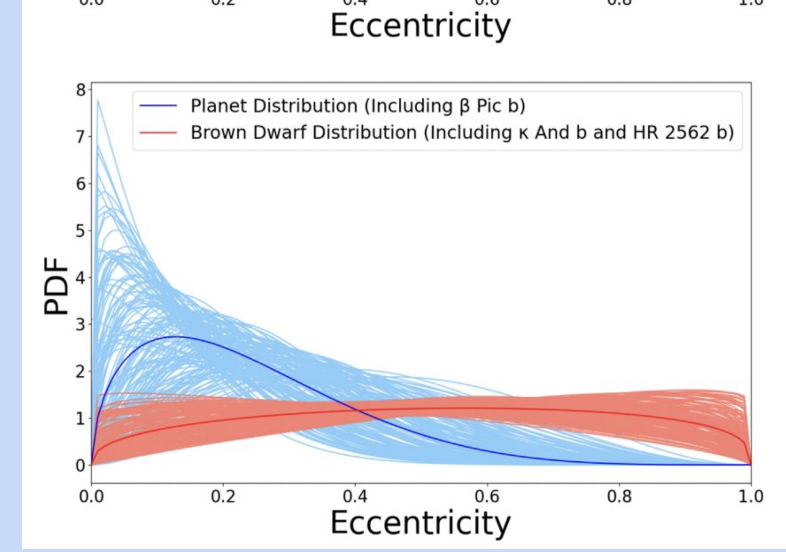
Bottom left: Inferred eccentricity distribution for directly imaged companions. The beta fit results (68th percentile) from sampling the posteriors are presented in the top panel. The distribution (dark blue) is plotted (bottom panel) with 100 distributions (light blue) that encompass our uncertainties. The lighter curves indicate the possible ranges of α and β from the fitting distribution.

Bottom right: Comparison of "planet" vs. "brown dwarf" distributions for different combinations of intermediate-mass objects: for our highest case (i.e., most similar distributions) and lowest case (i.e., most different distributions).

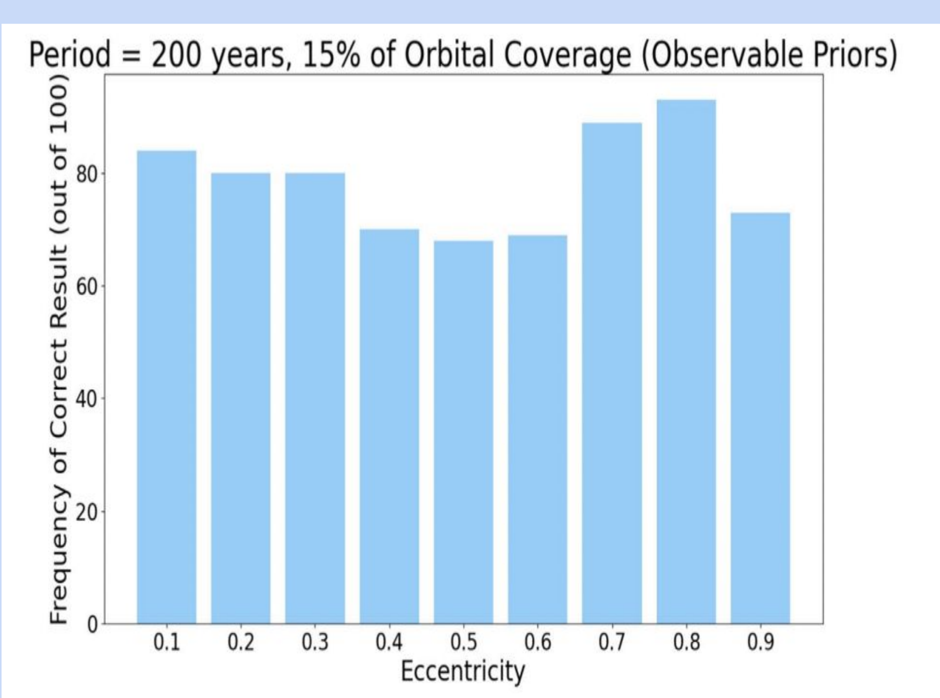


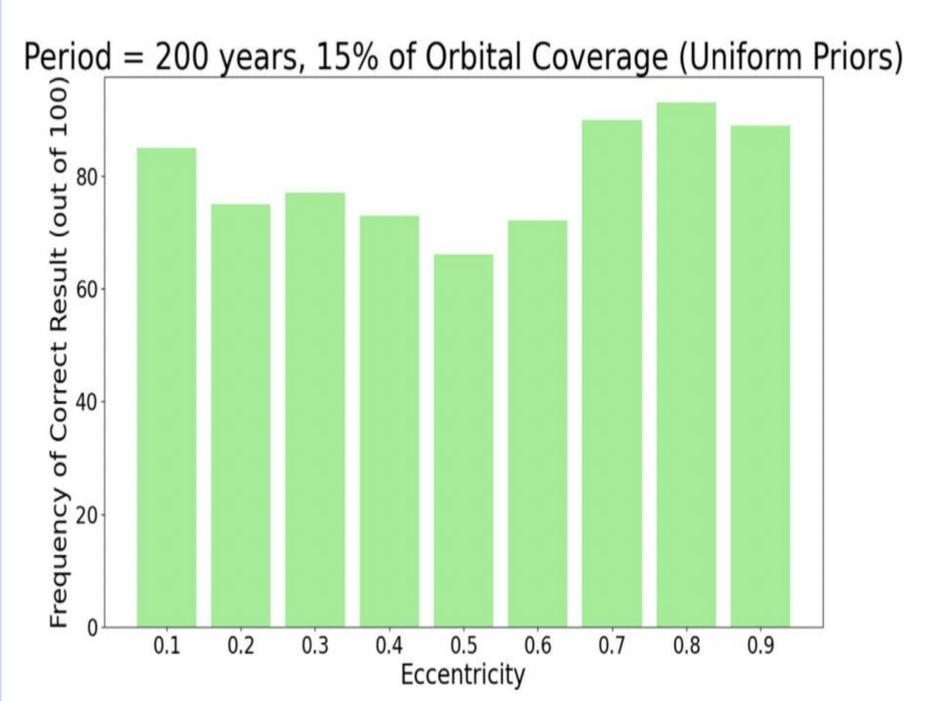






Orbital Coverage Simulations





Top: We find that the orbital coverage of 15% was the minimum value needed to obtain 68 successful posteriors (out of 100 trials) for both priors.

We simulate how much orbital period coverage we need in order to obtain a meaningful posterior distribution for eccentricity. We aim to stipulate whether we can obtain meaningful results on these objects with the currently available astrometry. **The average orbital period coverage for the sources in our sample is 7.4%**, (from weighted median values of our sample's orbital period fits and the astrometric coverage, in years, for each object in the sample). In our simulations, we:

- Generate astrometry points in order to simulate increasing orbital phase coverage.
- Run our observable prior and uniform prior orbit fitter 100 times for each orbital eccentricity value, increasing the astrometry and hence the phase coverage with each successive run.
- In order to consider a simulation "successful," the real input eccentricity, To, inclination and period must be within the 68% confidence interval given by the fit.

Conclusion

We derive new orbit posteriors for a set of 21 directly imaged substellar companions using observable-based priors, and find that several companions have eccentricity distributions that change significantly from previous results. We derive a population-level eccentricity distribution for the 21 companions. Our distribution is consistent with Bowler et al.'s (2020) parameters obtained using uniform priors, but with a lower incidence of high-eccentricity objects. We find that separating the population into "giant planets" and "brown dwarfs" produces different results depending on where intermediate-mass objects are placed.

This result implies that our sample size and large uncertainties may not be sufficient to determine whether these objects present distinct eccentricity populations. From our orbital coverage simulations, we find that one generally needs 15% orbital period coverage to obtain a reliable posteriors on eccentricity, period, and To posterior .