Radial Velocity Analysis of K2 Exoplanetary Systems using HIRES

Maleah Rhem (NSF-GRFP Fellow)[1] , Ian Crossfield[1] , Judah Van Zandt[2] , Erik Petigura[2] , Howard Isaacson[3] , Alex Polanski[4]

[1]University of Kansas, Lawrence, KS 66045
[2]University of California, Los Angeles, CA 90095
[3]University of California, Berkeley, CA 94720
[3]Lowell Observatory, Flagstaff, AZ 86001

Abstract

Transit and RV surveys have given us insight into the current distribution of exoplanets. Kepler revealed that short- period small planets have an occurrence rate of <1 planet per solar-type star, while RV surveys revealed that long-period giant planets near the snow line are less common. A few formation models of planetary system architectures with both types of planets have been proposed. However, the correlation between them has yet to be determined due to these short and long-period planets being discovered from stellar samples with different stellar distances. To fix this gap, NASA repurposed the Kepler spacecraft for the K2 mission, whose primary goal was to survey thousands of nearby, bright stars hosting short-period planets. Our goal is to detect long-period companions within these systems by looking for long-term RV trends from their host stars. This study analyzes the current RV trends collected from 27 K2 systems using the High-Resolution Echelle Spectrograph (HIRES) at the W.M. Keck Observatory. We are conducting a homogeneous analysis of these RVs to reveal new giant companions within each system and measure their occurrence rate within the overall sample. The discovery of these planets and their frequency in the Solar neighborhood will help us determine the correlation between small and giant planet formation.

Introduction

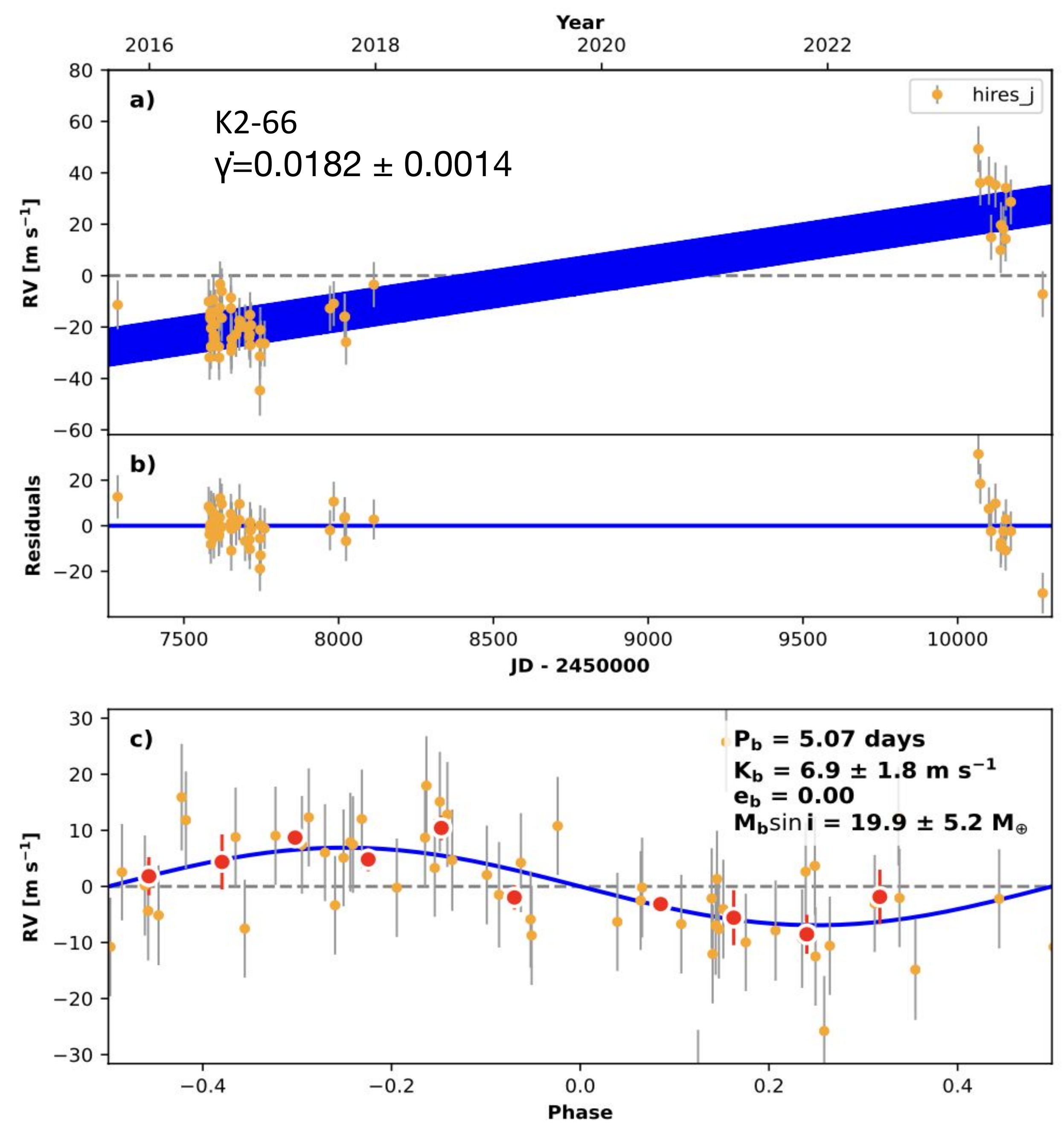
Massive companions on wide orbits serve as a signature for understanding planet formation. Kepler revealed that short-period small planets have an occurrence rate of <1 planet per solar-type star, while RV surveys revealed that long-period giant planets near the snow line are less common, with an occurrence rate of 5-10%. Additionally, the rate of short-period planets with giant companions is believed to be 10-30%. Studies suggest a possible positive correlation between small and large planet formation, if protoplanetary disks rich in solid materials lead to the formation of each planet's core both within and beyond the snow line. On the other hand, the correlation could be negative if the long-period giants either prevent the cores of the smaller planets from migrating inward or allow them to form within the snow line before they migrate closer to the host star. This correlation and its implications remain unresolved.

We are working to close this gap in our understanding of small-giant planet formation. The K2 mission detected many short-period planets around bright stars, with some of these systems undergoing RV follow-up in 2015-2017 with the High-Resolution Echelle Spectrograph (HIRES). We are seeking to identify long-term RV trends from these K2 host stars; i.e., linear stellar accelerations induced by larger objects. We observed these systems further with HIRES to extend the baseline of these systems from ~1 year to ~6-7 years to reveal giant companions on much wider orbits. **The goal of this study is to complete a homogeneous analysis of all RVs collected over the extended baseline to reveal new giant companions and measure their occurrence rate within the overall sample.**

Method

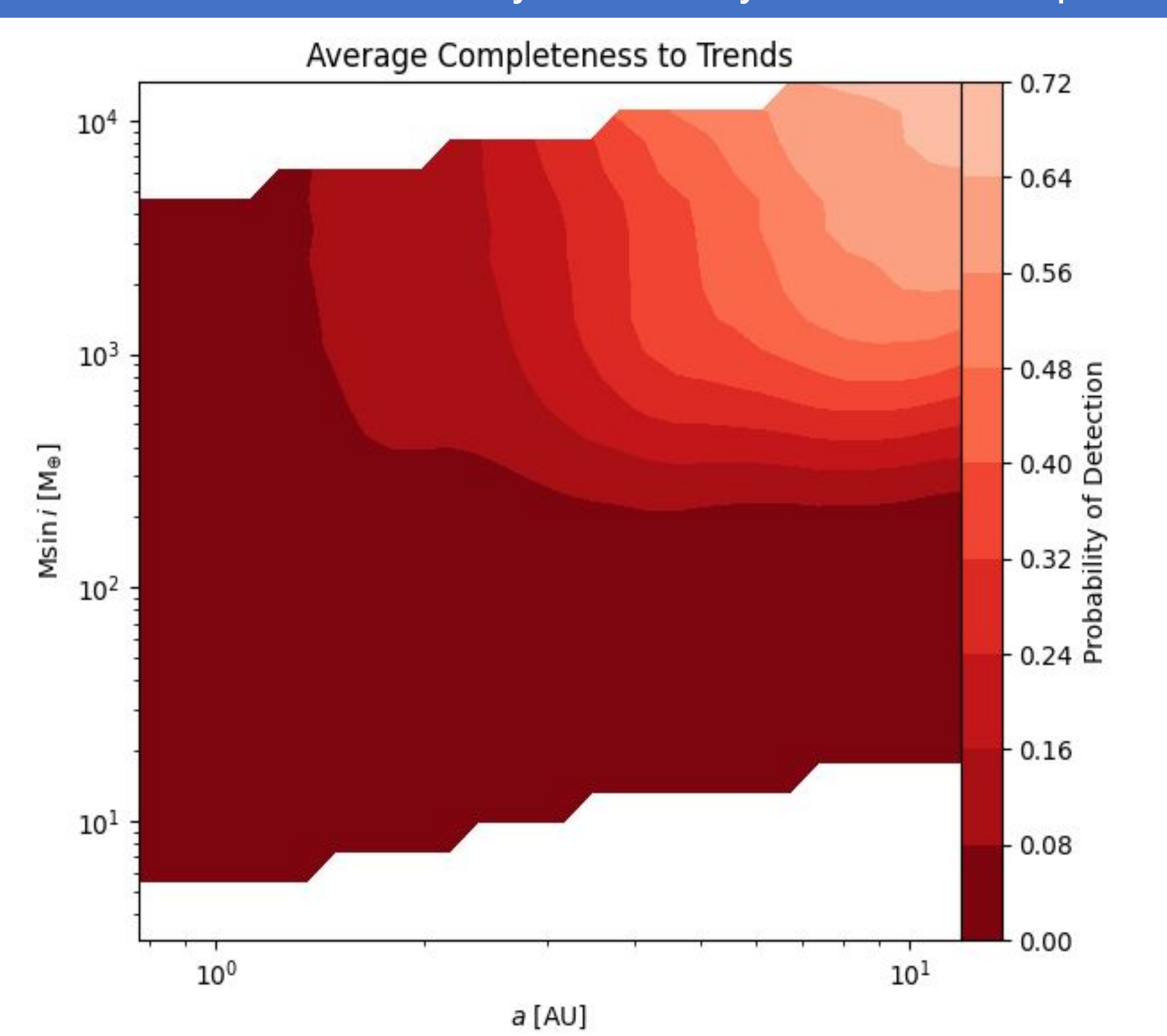
- We modeled and analyzed RV trends from 27 K2 targets using RadVel, a Python-based package used to model RV time series data. Our goal was to identify RV trends with a precision **≥ 3σ**.
- We used a modified version of RVSearch [3] by Dr. Judah Van Zandt to conduct injection/recovery tests on each target to assess our survey overall sensitivity to giant companions. RVSearch injected 2000 synthetic planetary RV signals and linear trends into each data set. Each injected planet's parameters include an RV semi-amplitude between 1 and 400 m/s with a period between 250 days and 15000 days.
- We used the Python package "ethraid" [4] to determine the possible masses and semi-major axes which induce our significant trends. To do so, ethraid takes each target's RV trend and average proper motion, samples prior distributions of six orbital parameters, including M=0.1-1000 M_Jup and a = 3-64 AU, and produces synthetic RV and astrometric data from the samples to compare to the data actually observed.

Result 1: 4 New Long Period Companions Identified



Our analysis of our HIRES RVs reveals at least **four new long-period companions** in our sample, each with long-term linear accelerations **of $\dot{\gamma}$ = -0.007 ± 0.001 for K2-108, $\dot{\gamma}$ = 0.0182 ± 0.0014 for K2-66, $\dot{\gamma}$ = 0.0092 ± 0.0025 for K2-234, and $\dot{\gamma}$ = 0.0106 ± 0.0014 for EPIC245943455, all with a trend significance ≥ 3σ. (Above)** Best-fit RV model for K2-66, with a) the best-fit 1-planet model, b) the model's residuals, and c) the RVs phase-folded to the ephemeris of the short-period planet with its best-fit orbital parameters.

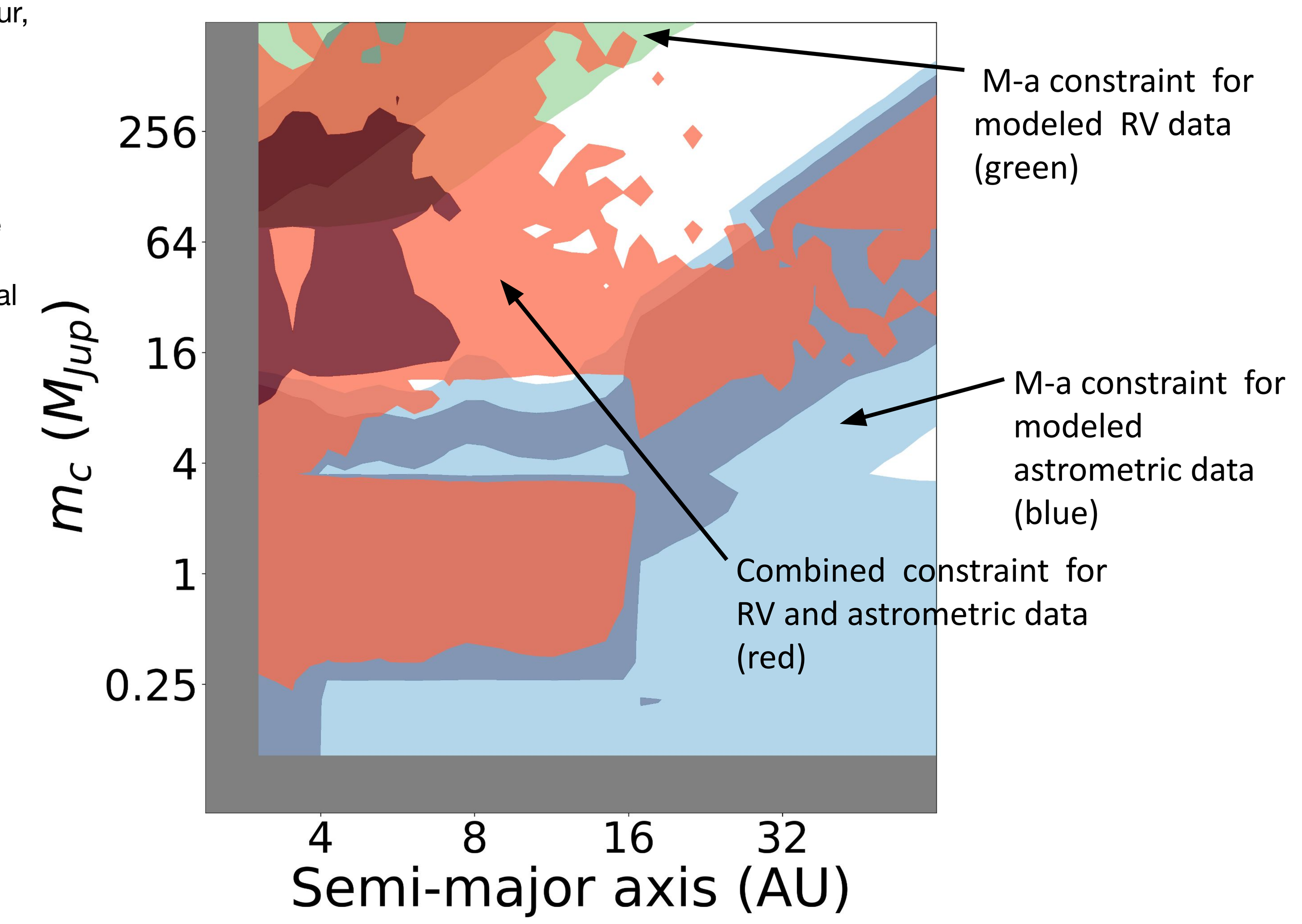
Result 2: K2-HIRES Survey Sensitivity to Giant Companions



Average completeness of all 27 targets. If the best-fit values for their orbital parameters match their original injected values by 25% or more, the algorithm considers the planet as recovered and plots that planet in M sin i-a space. For planets with masses up to 10,000 M⊕ and semi-major axes between 1-10 AU, our survey's sensitivity to giant companions inducing linear trends is at **14% completeness.**

Result 3: M-a Constraints for K2-234

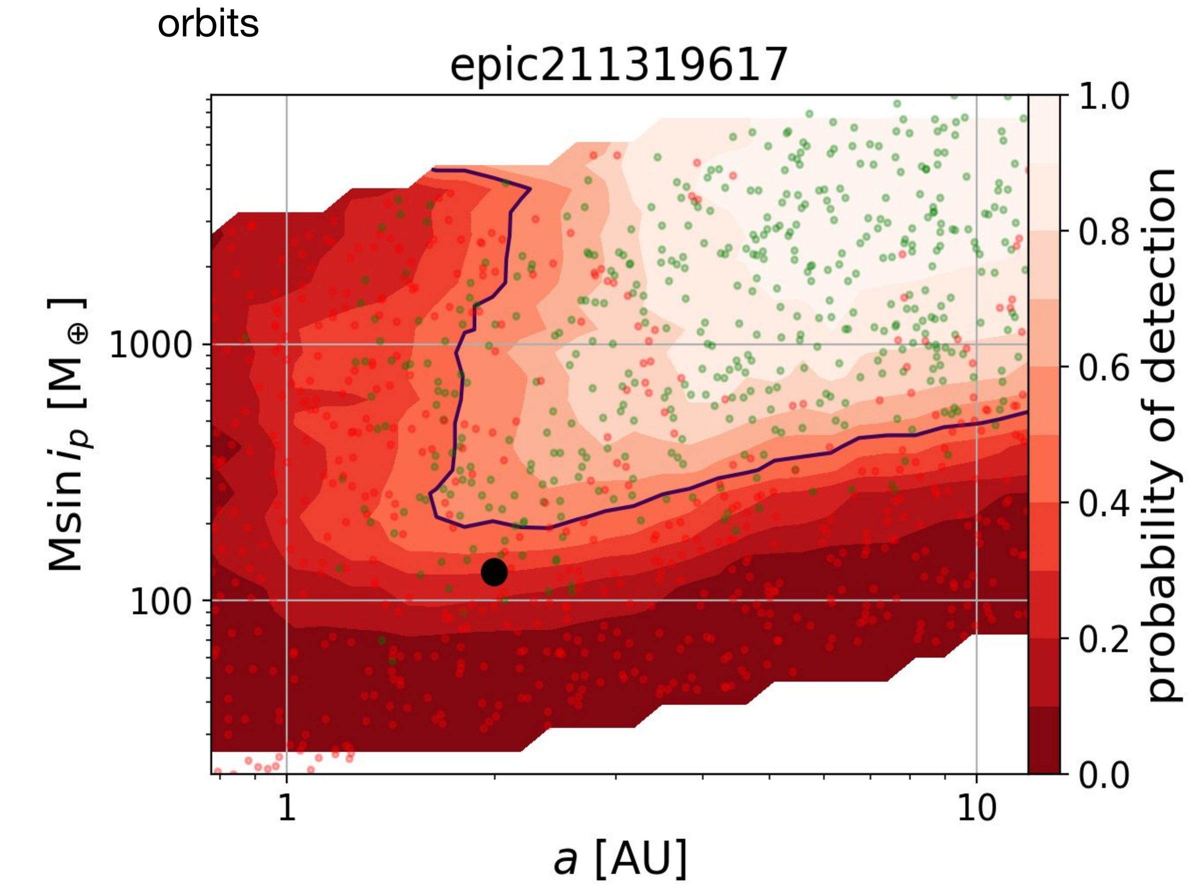
For each contour, the darker and lighter regions represent the 68% and 95% confidence intervals for the companion's mass and orbital separation.



M-a posteriors for K2-234 from ethraid (above), showing large overlap between the modeled RV and astrometric constraints, providing no precise constraint on the companion's mass and separation. Future work involves revisiting our analysis to better constrain the masses and orbital separations of this target's companion and our remaining significant trends.

Conclusions and Future Work - Allowing for Curvature

- We revealed 4 giant companions with a linear trend significance ≥ 3σ
- We found that the average completeness of our survey is 14% for companions detected by trends
- We also determined that searching for only linear trends lowers the completeness of our survey and
- Future work involves testing for curvature in our RV models and injection/recovery tests to push our sensitivity to lower mass giants on closer orbits



Example of an injection/recovery test on a simulated Cold Jupiter in K2-180 (EPIC211319617), allowing for synthetic linear and quadratic trends. The completeness for this target is 44%, which is much higher in comparison to 13% completeness without quadratic trends.

References

[1] Bonomo AS et al. 2023 A&A677 A33
[2] Fulton BJ et al. 2018 PASP130 044504
[3] Van Zandt et al. 2025 AJ 169 235
[4] Van Zandt & Petigura 2024 AJ 167 250
[5] Rosenthal et al 2021 ApJS 255 8

Acknowledgments

We would like to thank the W.M. Keck Observatory for allowing us to use their RV facility, HIRES. We'd also like to thank the NASA/Keck program for funding support for this study!