Predicting and Finding Temperate Terrestrial Planets as Habitable Worlds Observatory Targets

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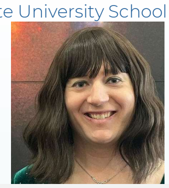


Abstract

We're likely missing ≳90% of the planets in the Solar Neighborhood, and some of those hidden planets are temperate terrestrial planets with a potential to host extraterrestrial life. But how can we efficiently locate these planets? Could they be hiding in already known systems? I investigated the orbital architectures and planetary characteristics of all nearby exoplanet systems and determined which are most likely to host a temperate terrestrial planet. Using the DYNAMITE software package I developed, I analyzed exoplanetary systems by combining the specific but incomplete observational data with population-level statistical models and constraints on system stability, and then predicted the presence and parameters of additional unseen planets. Current high-precision RV data will provide prioritized targets for extreme-precision radial velocity (EPRV) characterization and the future NASA flagship mission Habitable Worlds Observatory (HWO) searching for biosignatures, potentially bringing us significantly closer to finding life elsewhere in the universe.

Introduction

The *Kepler* transit survey mission supplied us with the first planet population able to be studied demographically, providing a better understanding of the big picture of exoplanet system architectures. We can now examine what types of planetary systems exist in the universe and gather information on what might be the most typical system we will find around a given star. Using planetary occurrence rates and statistical planet parameter distributions, we can even predict the most likely planet that exists but has not yet been found. Following up with targeted observations will allow us to find additional planets that may be missing, as well as assess the accuracy of the current models. We can use this information to help prioritize the target list for the HWO, which will be designed to directly image temperate terrestrial planets and search for signs of life.

Methodology

Here I utilized the software package DYNAMITE (DYNAmical Multi-planet Injection TEster) that I created to analyze multi-planet systems.

- Input: Orbital periods, planet sizes (radius and/or mass/m sin i), orbital inclinations, and orbital eccentricities
- Analysis: Monte Carlo iterations of the system using Kepler population statistics and a dynamical stability criterion
- Output: Likelihoods for each input parameter for one additional planet in the system. These are then used to calculate expected observable signatures of the predicted planet (transit probability + depth, RV semi-amplitude, direct imaging separation + contrast)

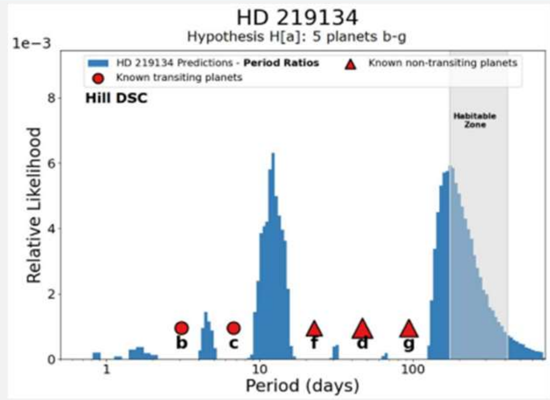
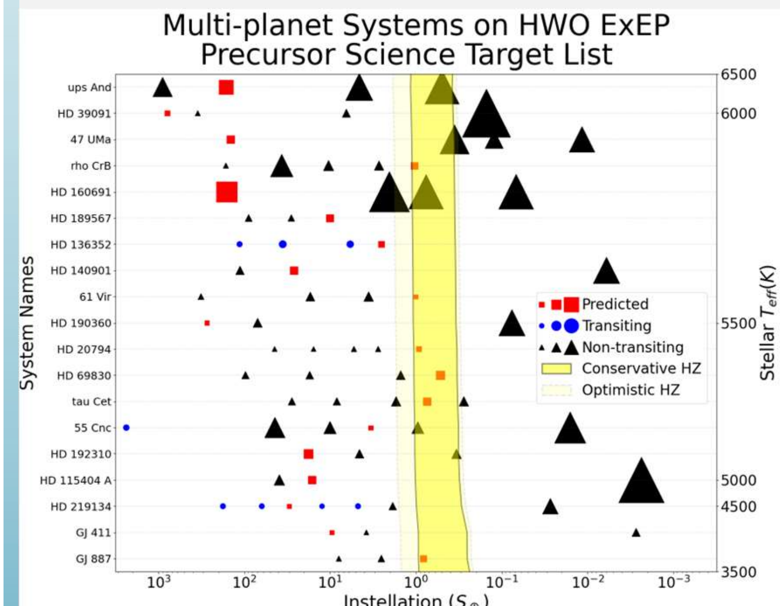


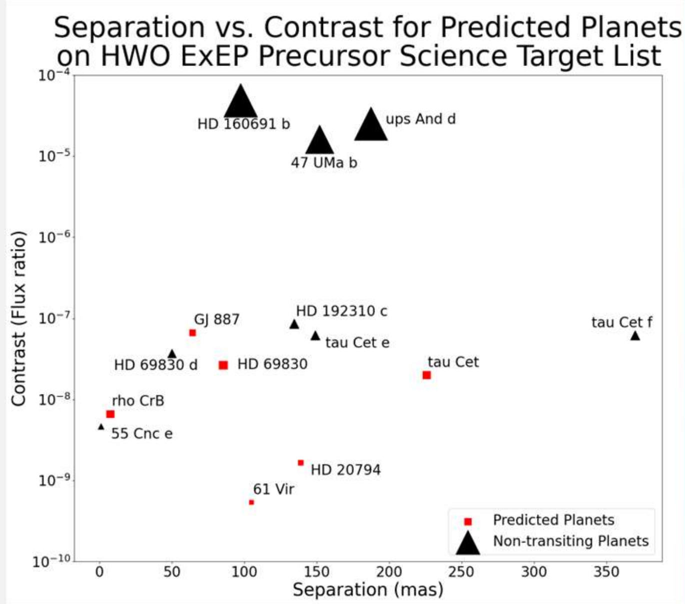
Figure from Dietrich, Apai, and Malhotra (2022); orbital period likelihood for an additional planet in the HD 219134 system with five inner planets. It is roughly equally likely that an additional planet would exist with a period of ~12 days and a period of ~180 days.

Results

There are 19 known multi-planet systems on the HWO Precursor Target List, more than 10% of the current selection. Of the two around early M dwarfs , one is predicted to have a terrestrial planet in the conservative habitable zone (HZ). Two of the four systems around K dwarfs have at least a Neptune-sized planet within the conservative habitable zone, while the others have large gaps where they could potentially host at least one temperate terrestrial planet. Finally, five of the 13 G dwarfs are predicted to host a super-Earth to super-Neptune planet (depending on the inclination of the system and the expected masses of the known planets) within the habitable zone, while an additional three host gas giants in the habitable zone.



The 19 multi-planet systems on the HWO Precursor Science Target List, ordered by stellar effective temperature and with known and predicted planets/candidates ordered by effective instellation. Marker size corresponds to the radius (if known) or mass/m sin i for each planet.

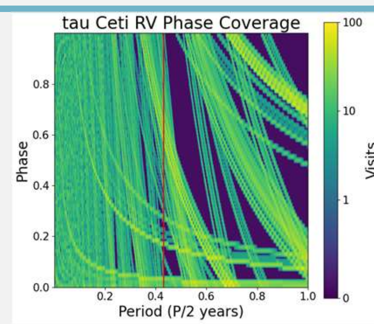


Known and predicted planets / planet candidates within the optimistic HZ as defined at left. Three are gas giants and so are unlikely to be HWO targets, but the remaining ones are Neptune-sized and below, with one known and three predicted super-Earths.

Discussion

A large majority of nearby planetary systems that could host temperate terrestrial planets are around M dwarf stars. While M dwarfs are the best stellar hosts for finding small planets, they are not the best targets for direct imaging due to the extremely small separation of the habitable zone. Thus, the K- and G-star HWO Precursor Science targets above would be the best targets for imaging.

Focused EPRV observations will be able to help rank Precursor Science targets for HWO by confirming and characterizing temperate terrestrial planets with sufficient angular separation. However, for mid- to early-G stars specifically, the temperate zone of the star coincides with that of our own sun, making RV detections much more difficult due to the annual systematic of the Earth's orbit. Some HWO targets, like tau Ceti shown at right, have been extensively searched for additional planets with RV over multiple years, but a more uniform targeting of the highest-priority targets will provide the best chance of finding a temperate terrestrial planet with biosignatures.



Phase coverage of tau Ceti from NEID and EXPRES observations. The red line corresponds to the predicted planet's orbital period, which has 10-100 visits at a large majority of the orbital phase, providing a tighter upper limit on the existence and mass of such a planet.

Conclusions

- >10% of HWO Precursor Science Target List hosts multiple planets
- Of the 19 multi-planet systems, 4 could potentially host a temperate terrestrial planet
- Targeted EPRV observations will find and characterize the best planets for imaging with HWO

References

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