Using the Titius-Bode Relation to Correct for Kepler Incompleteness in the Habitable Zone

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Using the Titius-Bode Relation to Predict the Periods of Kepler's Missing Planets

What is the Titius-Bode relation (TBR)

- The TBR was used to help discover the Asteroid Belt and Neptune, Uranus could have been discovered earlier by using the relation, which was known at the time.
- The TBR represents the approximately even logarithmic spacing of planetary orbital distances or periods.
- The relation is directly related to the period ratios of adjacent planets in the same system, which it predicts will be approximately constant: $P_{n+1}/P_n \approx C$ for all planets pairs in the system.
- For adjacent planet pairs which do not have a period ratio near this common value, we assume there is at least one undetected planet between the planet pair and insert planets to increase the system's adherence to the TBR (Figs. 1 and 2)

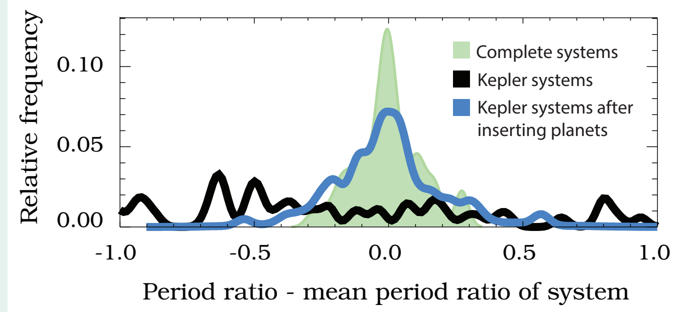

Figure 1: Period Ratios as a Proxy for Completeness The distribution of adjacent planet period ratios, offset from the mean period ratio in each system. The green distribution represents our 'most complete' systems (unlikely to contain undetected planets). The black distribution indicates that the sampling of Kepler systems is highly incomplete. The blue distribution represents the same systems after missing planets have been inserted using the Titius-Bode relation.

- The transiting planetary systems discovered by the Kepler mission are subjected to significant selection effects as the probability of a planet transiting falls off with increasing period.
- We expect many Kepler systems to have a high degree of incompleteness, as only some fraction of the planets around a star will transit while the other planets remain undiscovered.
- Previous period predictions that we have made resulted in the discovery of five new transiting planets.

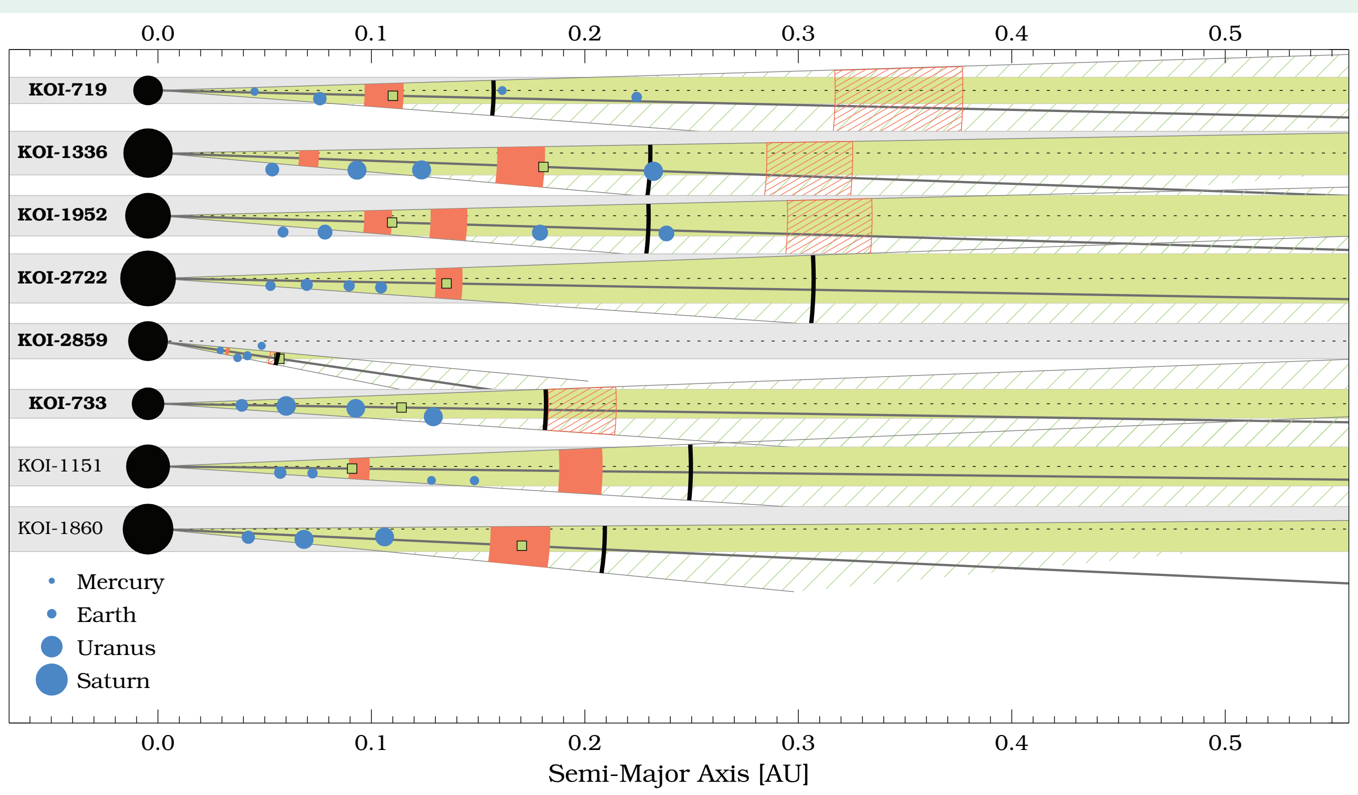

Figure 2: Detected Planets Based on Titius-Bode Relation Predictions
Exoplanet systems where an additional candidate was detected after a TB relation prediction was made. Previously known planets are shown as blue circles. The predictions of Bovaird and Lineweaver (2013) and their uncertainties are shown by the red filled rectangles if the transit probability is high, or by red hatched rectangles otherwise. The new candidate planets are shown as green squares. The critical semi-major axis, beyond which the probability for a planet to transit is < 0.5, is shown by a solid black arc.

The Average Number of Planets in the Habitable Zone Per Star

What is the Probability of a Predicted Planet being Rocky?

- We define a 'rocky' planet by its radius, with planets having $R_p \leq 1.5\ R_\oplus$ being assumed to be rocky (Rogers et. al. 2014).
- The Titius-Bode relation directly gives a period for the predicted planet. We look at the period ratios between adjacent planets and the dynamical stability of the system to add an uncertainty to the predicted period.
- Given the predicted planet period, the noise of the star, and the size of the detected planets in the system, we calculate the maximum radius of the predicted planet which would have resulted in a detection. The predicted planet must therefore have a radius less than this value R_{max}.
- We use an assumed planetary radius distribution (Fig. 3), and calculate the fraction of the "undetectable" and "detectable" regions which are $\leq 1.5\ R_\oplus$.

  This fraction is the probability of the predicted planet being rocky, i.e. what fraction of the parameter space not excluded by observations lies in the region where the planet is likely to be rocky ($R_p \leq 1.5\ R_\oplus$).

~0.3 Rocky Planets Per Star in the Habitable Zone ($R_p \leq 1.5\ R_\oplus$)

- For the 31 systems in our sample which have planets close to the habitable zone, we use the Titius-Bode relation to account for the expected detection incompleteness and insert the missing, undetected planets.
- We extrapolate the planetary spacing of the system such that it extends past the outer edge of the habitable zone.
- We then calculate the probability of being rocky for each of these extrapolated planets.
- On average, there are 2±1 planets in the habitable zone per star, almost independent of our three definitions of the habitable zone (Table 1 & Fig. 4).
- Of the 2±1 planets in the habitable zone per star, we expect ~0.3 to be rocky

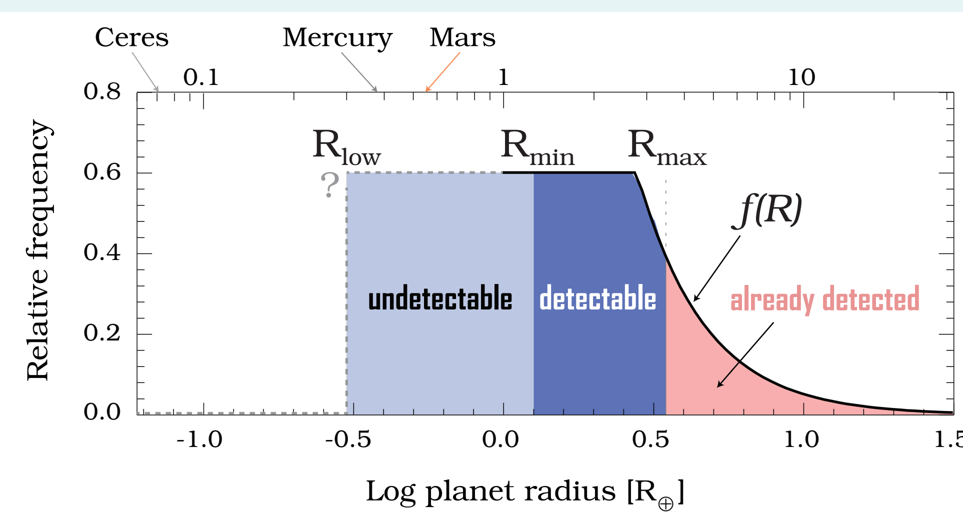

Figure 3: Planet Radius Distribution
Our assumed planetary radius distribution. The distribution is well known above 1 Earth Radius but poorly constrained below this value (Howard et. al. 2011, Foreman-Mackey et. al. 2014). The three regions represent planets that Kepler would have already detected, planets that Kepler may still detect and planets that Kepler will not be able to detect, for a given star and period.

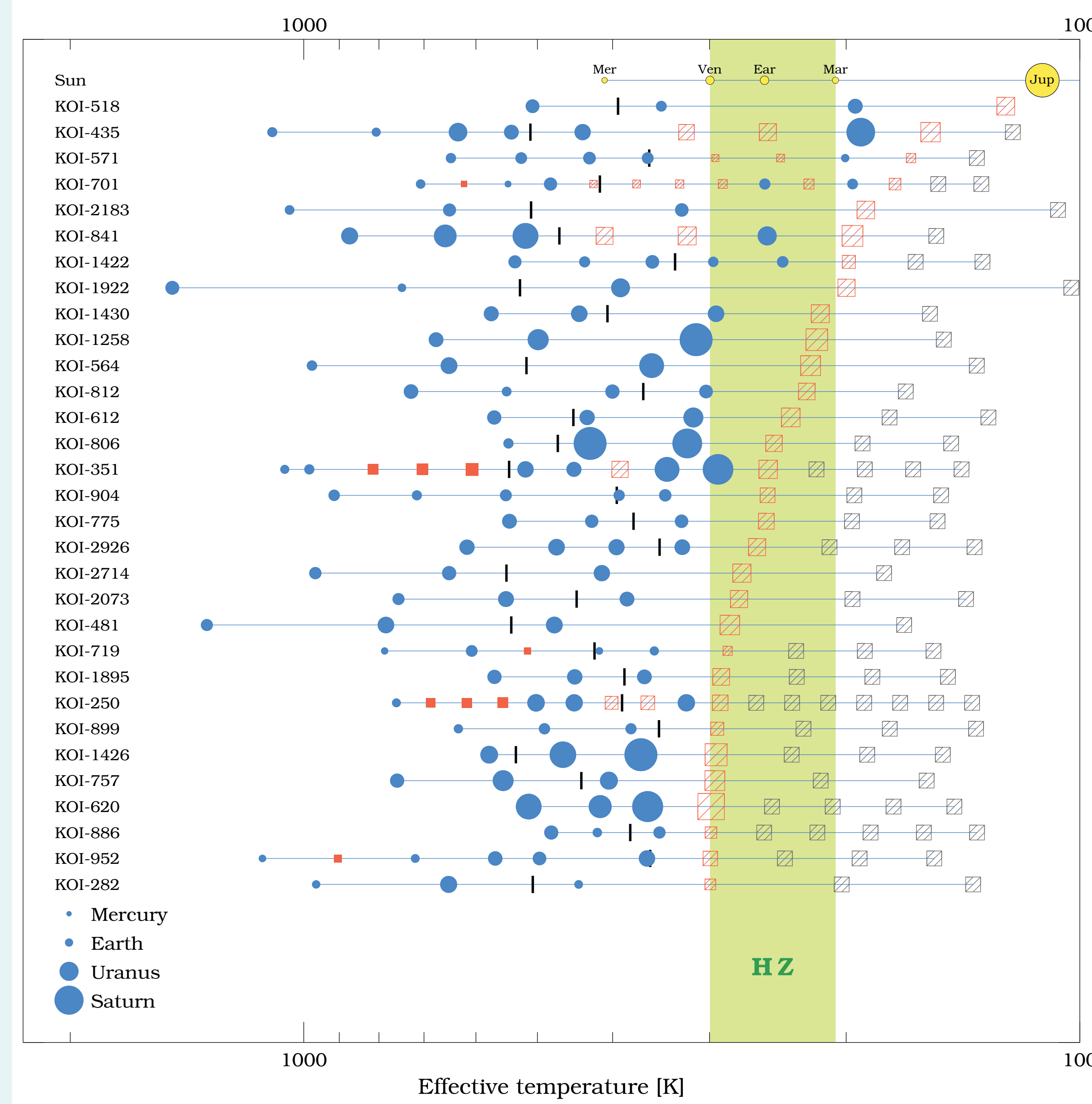

Figure 4: Extrapolating Predictions to Estimate the Number of Habitable Zone Planets Per Star
The effective temperatures of planets within the 31 systems from our sample which extend out to the green habitable zone (HZ) after our planet predictions are made. For the purpose of estimating the number of HZ planets per star (see Table 1), we extrapolate additional planets (gray squares) beyond the HZ. The sizes of the red hashed squares represent the maximum radius of the predicted planet.

Table 1. The estimated number of planets per star within various 'habitable zones'.

	All planets			Rocky planets ($R \leq 1.5\ R_\oplus$)		
Sample	Mars-Venus	K13 "optimistic"	K13 "conservative"	Mars-Venus	K13 "optimistic"	K13 "conservative"
All 151 systems	2.0± 1.0	2.3± 1.2	1.5± 0.8	0.15	0.15	0.10
Least extrapolation [b]	1.6± 0.9	1.7± 0.8	1.3± 0.7	0.40	0.35	0.30

[a] K13 "optimistic" and "conservative" habitable zones refer to the "recent Venus" to "early Mars" and "runaway greenhouse" to "maximum greenhouse' regions from Kopparapu et al. (2013) respectively'.
[b] The 31 systems in the sample shown in Fig. 4 are those which need the least extrapolation (red hashed squares) to extend out to (or beyond) the green Mars-Venus HZ.

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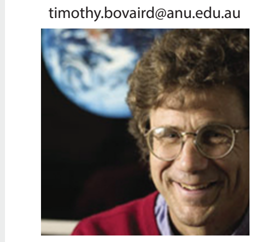

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