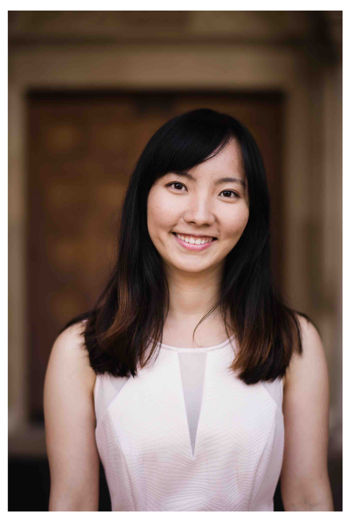

An Increase in Small-planet Occurrence with Metallicity for Late-type Dwarf Stars in the Kepler Field and Its Implications for Planet Formation

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There must be a threshold for the amount of solid material in a protoplanetary disk below which even small planets cannot form. Since the amount of planet-making material in a protoplanetary disk is proportional to host star metallicity and mass, the best way to search for this effect is to calculate the planet occurrence for metal-poor, low-mass stars. For late K and early M dwarfs, we have calculated the effect of stellar metallicity on planet occurrence in the Kepler DR 25 KOI list. We find that for late-type stars, the probability of hosting a small planet increases with stellar metallicity. For planets in the range $2\,R_\oplus < R_p < 5\,R_\oplus$, we show that a 0.3 dex increment in [M/H] increase planet occurrence by a factor of two. This implies that small planet occurrence increases linearly with stellar metallicity Z. This result demonstrates the importance of metallicity in the calculation of small planet occurrence and therefore for TESS yield calculations. We predict that for early M dwarfs at [M/H] = −1, even super-Earth planets should be rare.

We confirm the theoretical expectation that the small planet occurrence-host star metallicity relation is stronger for low-mass stars than for solar-type stars. We establish that the expected solid mass in planets around late-type dwarfs in the Kepler field is comparable to the total amount of planet-making solids in their protoplanetary disks. We argue that this high efficiency of planet formation favors planetesimal accretion over pebble accretion as the origin of the small planets observed by Kepler around late-type dwarf stars.

Input Data

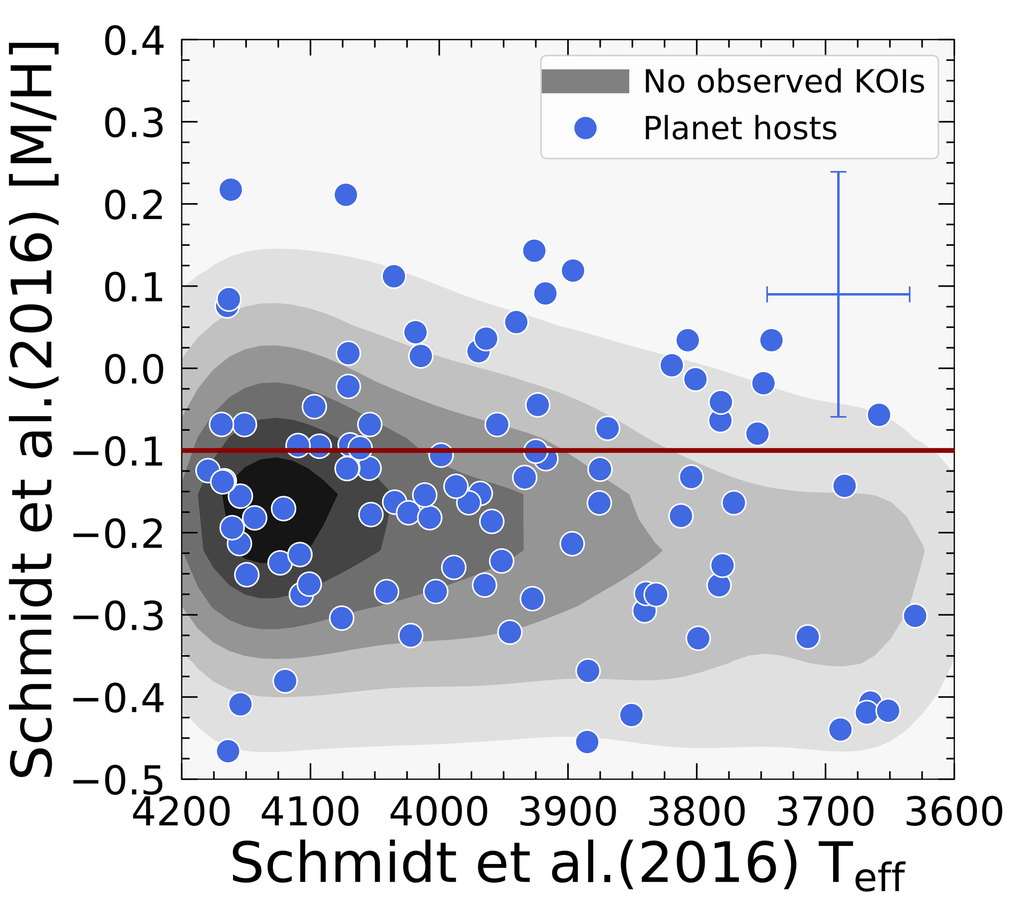

Figure 1. Plot of [M/H] versus T_{eff} for late-type dwarf Kepler targets calculated according to the photometric metallicity and temperature relations optimized for late-type dwarfs detailed in Schmidt et al. (2016). The blue points are individual KOI host stars, while the background contours show the distribution of a control sample of late-type dwarf Kepler targets without observed KOI. The red line separates the KOI host sample into metal-poor and metal-rich subsamples with equal numbers of KOI. The same cut is applied to the control samples used for the occurrence calculations illustrated in Figure 2. The error bar in the upper right gives the typical uncertainty of an individual estimate.

Small Planet Occurrence for Different [M/H]

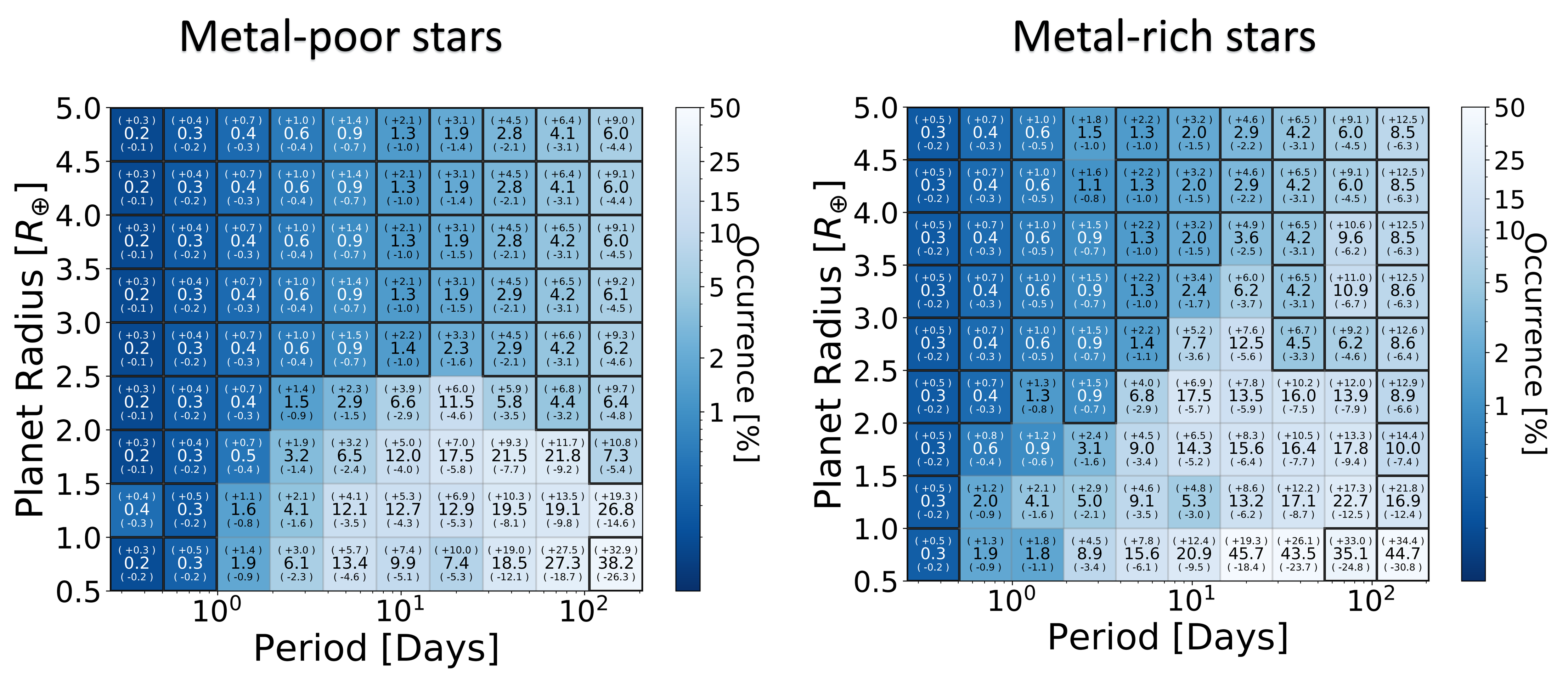

Figure 2. Planet candidate occurrence in metallicity–period–planet radius space with an uninformative prior. The values in each cell are the occurrence of planet candidates in that cell and its uncertainty. All values are expressed as percents. Cells with heavy borders have no detected planet candidates. **Left**: small planet candidate occurrence in our metal-poor subsample. **Right**: small planet candidate occurrence in our metal-rich subsample. Planet candidates are significantly more common in the metal-rich subsample than in the metal-poor subsample. The product of our samples' sizes and Kepler DR25's completeness indicate that the amount of information implicit in a non-detection is at least a factor of five larger than the signal weakly implied by our prior for cells with P $\leq$ 100 days and $R_p \leq 1\,R_\oplus$.

Implications

Sample	Expected Mass in Planets ($M_\oplus$)	Expected planet-making material in the protoplanetary disks ($M_\oplus$)
Metal-poor	$16.5^{+0.6}_{-1.8}$	14
Metal-rich	$24.5^{+0.9}_{-2.5}$	28
Complete	$13.9^{+0.5}_{-1.2}$	20

Table 1. Expected mass in planets and Expected planet making material in the disk as a function of metallicity. Expected mass in planets is calculated using mass–radius relation presented in Ning et al. (2018) and implemented in the MRExopackage (Kanodia et al. 2019). We estimate the expected mass of planet-making material in the protoplanetary disks using the solids fraction in protoplanetary disks observed by Andrews et al. (2013).

We find planet formation efficiencies in excess of 50%.
2 possibilities:
- planet formation is very efficient or
- the small planet candidates observed around the Kepler field's late-type dwarf stellar population formed in disks more massive than the average disks observed by Andrews et al. (2013).

Results: For $2\,R_\oplus \leq R_p \leq 5\,R_\oplus$ planets, the occurrence scales linearly with metallicity

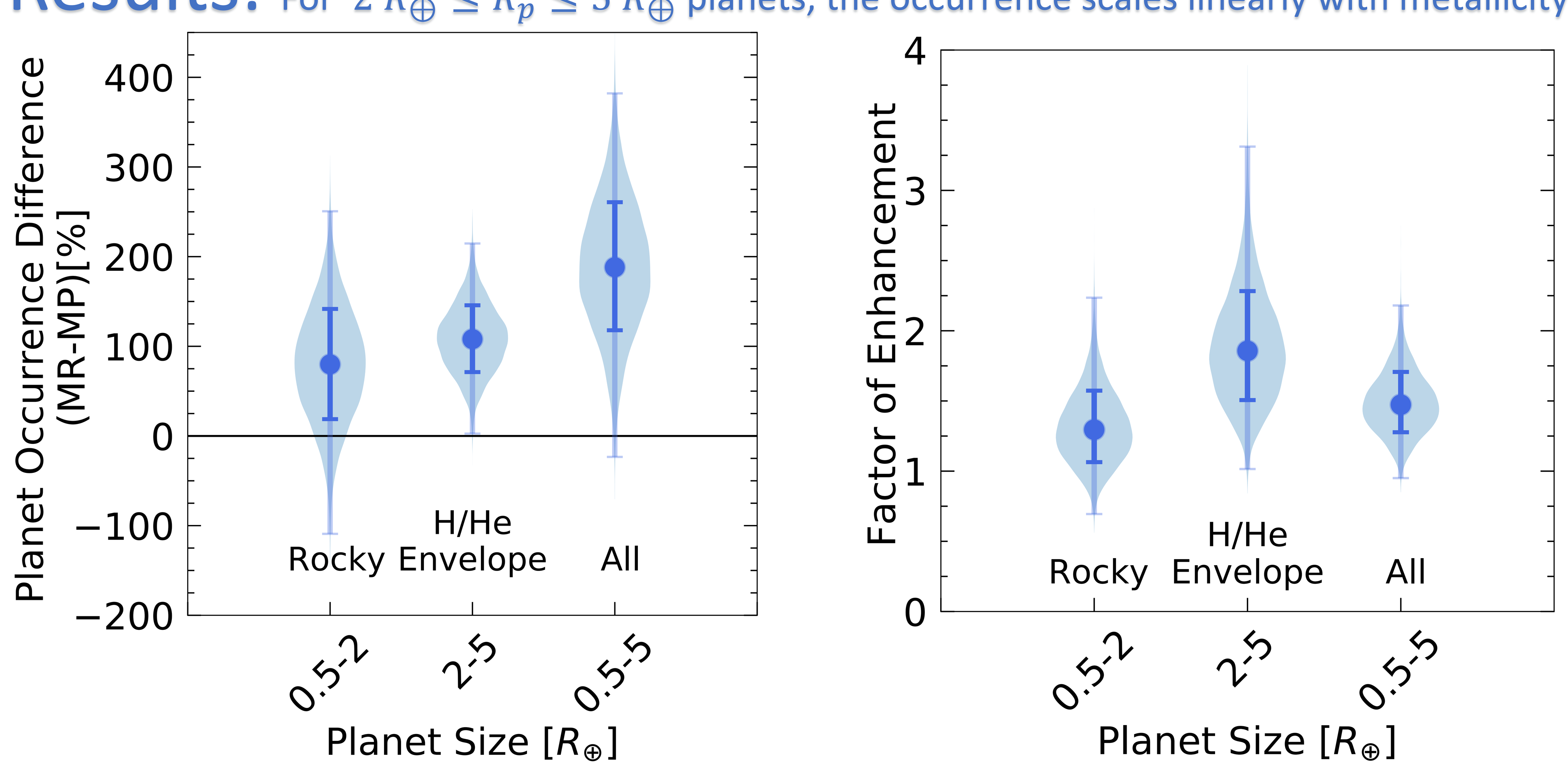

Figure 3. Violin plots with differences in planet candidate occurrence between metal-rich and metal-poor subsamples as a function of planet radius. The dark blue bars denote the 16th and 84th percentiles (i.e., the 1σ region) while the light blue bars represents the 0.13th and 99.7th percentiles (i.e., the 3σ region).
Left: planet occurrence difference as a function of planet radius. **Right**: factor of enhancement as a function of planet radius. The occurrence of planet candidates is significantly higher in our metal-rich subsample both for the entire range of radii we study $0.5\,R_\oplus \leq R_p \leq 5\,R_\oplus$ and for H/He envelope planets with $2\,R_\oplus \leq R_p \leq 5\,R_\oplus$. Our results are inconclusive for rocky planets with $0.5\,R_\oplus \leq R_p \leq 2\,R_\oplus$.