Photoevaporation and High-Eccentricity Migration Created the Sub-Jovian Desert

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3 July 2018

ABSTRACT
The mass-period or radius-period distribution of close-in exoplanets shows a paucity of intermediate mass/size (sub-Jovian) planets with periods $\lesssim 3$ days. We show that this sub-Jovian desert can be explained by the photoevaporation of highly irradiated sub-Neptunes and the tidal disruption barrier for gas giants undergoing high-eccentricity migration. The distinctive triangular shape of the sub-Jovian desert result from the fact that photoevaporation is more effective closer to the host star, and that in order for a gas giant to tidally circularise closer to the star without tidal disruption it needs to be more massive. Our work indicates that super-Earths/mini-Neptunes and hot-Jupiters had distinctly separate formation channels and arrived at their present locations at different times.

Key words: planets and satellites: dynamical evolution and stability – planets and satellites: formation

1 INTRODUCTION
Exoplanet detections have grown at a tremendous rate over the last decade. The exoplanet population has now reached the point where one can search the distribution of exoplanet properties for trends which could elucidate their origins. One of the interesting results to emerge is the presence of planets with short orbital periods ($\lesssim 2.5$ days). There is a well known pile-up of giant planets with periods around 3 days (e.g. Cumming et al. 2008; Howard et al. 2010); these are the “hot-Jupiters”. Lower mass and smaller planets ($R_p \sim 1 - 4 R_\oplus$) have now been found in abundance at short periods as well (e.g. Borucki et al. 2011; Pressin et al. 2013; Petigura et al. 2013; Silburt et al. 2015; Mulders et al. 2016).

However, planets do not populate all regions of parameter space at short periods. Szabó & Kiss (2011) first identified a lack of intermediate mass planets ($0.02 < M_p < 0.8 M_J$) at short periods ($P \lesssim 2.5$ days), which they labelled the “sub-Jupiter desert”. Working with a planet sample for which the stellar-parameters have been determined accurately using asteroseismology, Lundkvist et al. (2016) identified a region in the planet radius-period plane that was devoid of moderate sized ($2 - 4 R_\oplus$) planets at short periods (Beaugé & Nesvorný 2013) and subsequently Mazeh et al. (2016) studied the trends in both the planet mass-period and the planet radius-period planes, showing this hot sub-Jovian desert was present in both data sets. Furthermore, Mazeh et al. (2016) showed that the desert consisted of two boundaries: one at high mass/large radius, where the planet’s mass/radius decreases with increasing semi-major axis, and another at low mass/small radius, where the planet’s mass/radius increases with increasing semi-major axis.

Until recently, the Kepler planet candidate catalogue contained false-positives that made it difficult to study the desert in the planet radius-period plane. However, using statistical vetting of planet candidates Morton et al. (2016) removed many of the false positives. The removal of these false positives showed that the desert of intermediate sized planets was very clean. Recently, it has also been identified that the small (Neptune/sub-Neptune sized) planets close to the lower boundary are more common around higher metallicity stars (Dong et al. 2017; Petigura et al. 2018). This increased occurrence rate of hot Neptunes around metal-rich stars has been interpreted as evidence for high-eccentricity migration of Neptunes (Dong et al. 2017) or metallicity dependent photoevaporation (Owen & Murray-Clay 2018).

Understanding the origin of these features would illuminate the origin of close-in planets. Several formation mechanisms for these planets have been studied. Many authors (e.g. Hansen & Murray 2012; Chatterjee & Tan 2014; Lee et al. 2014; Lee & Chiang 2016; Mohanty et al. 2017) suggested that low-mass super-Earths/mini-Neptunes formed in situ, close to their current orbital locations, while Batygin et al. (2016) suggested that hot-Jupiters could also have formed in-situ. On the other hand, disc-driven migration may have played an important role in the
formation of all close-in planets (e.g. Ida & Lin 2008; Mor- hasini, Allbert, & Benz 2009). For hot Jupiters, an appealing formation channel is high-eccentricity migration, in which the planet is pumped into a very eccentric orbit as a result of gravitational interactions with other planets or with a distant stellar companion, followed by tidal dissipation which circularises the planet’s orbit (e.g., Wu & Murray 2003; Fabrycky & Tremaine 2007; Nagasawa, Ida & Beuvoir 2008; Wu & Lithwick 2011; Beauge & Nesvorny 2012; Naoz et al. 2012; Petrovich 2015; Anderson, Storch & Lai 2016; Munoz, Lai & Liu 2016). However, the origin of the hot sub-jovian desert remains unclear.

Owen & Wu (2013) and Lopez & Fortney (2013) studied the photoevaporation of low-mass planets that were present at short-periapsis at early times and showed that the shape of the lower-boundary in the radius-period plane was consistent with photoevaporation of the H/He atmospheres of initially low-mass planets (\(\lesssim 20\ M_\oplus\)). Additionally, Jackson et al. (2012) and Kurokawa & Nakamoto (2014) suggested photoevaporation was important in sculpting the mass distribution of close-in giant planets. Specifically, Kurokawa & Nakamoto (2014) hypothesised that vigorous photoevaporation of short-period giant planets could trigger Roche-lobe overflow, leaving behind either giant planets massive enough to survive photoevaporation/Roche-lobe overflow or completely photoevaporated solid cores. Alternatively, Mat-sakos & Königl (2016) proposed that the entire sub-Jovian desert was created by tidal disruption of planets in the high-eccentricity migration scenario, with the upper and lower boundaries of the desert corresponding to different mass-radius relation of planets.

The recent detection of a gap in the planetary radius distribution of small planets (Fulton et al. 2017) confirmed that photoevaporation does indeed play an important role in the evolution low-mass planet population (Owen & Wu 2017; Van Eylen et al. 2017). However, detailed radiation-hydrodynamic photoevaporation models (e.g. Murray-Clay et al. 2009; Owen & Jackson 2012; Tripathi et al. 2015; Owen & Alvarez 2016) indicate that strong photoevaporation of giant planets is difficult, and removing a giant planet’s entire H/He atmosphere is impossible, even at the shortest orbital periods.

In this work we explore both photoevaporation and tidal stripping/disruption that results from high-eccentricity migration as possible origins of the sub-Jovian desert. Specifically we examine the upper and lower boundaries in the planet radius - period and mass - period distributions. We show that a combination of photoevaporation for low-mass planets and tidal disruption for massive planets is required to explain the observation.

2 PLANET SAMPLE AND MODELS

2.1 Planet Sample

We chose to represent the location of the planet by its orbital period rather than semi-major axis. This is because the long-term evolution of a planet undergoing photoevaporation depends on the total amount of high-energy flux it receives over its lifetime, which is best represented by a planet’s orbital period when considering a range of stellar masses (Owen & Wu 2017) and the period at which a planet is tidally disrupted is independent of stellar mass.

We use the confirmed exoplanet database from the NASA planet archive. We place a wide mass-slab cut on the sample, retaining those planets whose stellar hosts have masses between 0.4 and 1.6 M\(_\odot\). We show the radius-period and mass-period exoplanet population in Figure 4. Both plots exhibit a clear sub-jovian desert. In cases where only M\(_p\) sin\(i\) is measured we show this value as the planet’s mass (the square symbols in the bottom panel of Figure 4). Note that in the radius-period plot (upper panel), two classes of “misleading” planets appear in the desert: (1) The triangles indicate disintegrating rocky planets, (e.g. Rappaport et al. 2012; Sanchis-Ojeda et al. 2015), where the surface temperatures are large enough to allow sublimation of the planet’s surface. This sublimated rock can then escape the planet’s gravity in a hydrodynamic outflow, before cooling and re-condensing to form dust. (Perez-Becker & Chiang 2013). This dusty outflow then gives the planet a much larger apparent radius. (2) The crosses represent planets that appeared in the confirmed exoplanet database, but have subsequently been suggested to be background eclipsing binaries (Capra et al. 2017).

2.2 Planetary structure and evolution models

Throughout this work we will require an understanding of how the radius of a planet of a given composition varies with both its mass and temperature. To achieve this we follow Owen & Wu (2013), Owen & Menou (2016), Chen & Rogers (2016) and use the MESA stellar and planetary evolution code (Paxton et al. 2011, 2013, 2015) to numerically determine the structure and evolution of a planet. Our planets consist of a solid core composed of 1/3 iron and 2/3 silicates whose radius is determined following the mass-radius relationship of Fortney et al. (2007); this solid-core is surrounded by a Hydrogen/Helium envelope, with the envelope-mass fraction (X) given by the ratio of the envelope mass and the core mass. For each core-mass and envelope mass we select models with initial cooling times in the range 1 to 50 Myr and calculate the evolution of all these models. While the initial cooling can have a small impact on the planet’s thermal history (see discussion in Owen & Wu 2013), the exact value of the cooling time does not affect the results and conclusions of our work. We use the photoevaporative mass-loss rates calculated by Owen & Jackson (2012), following the method set out in Owen & Wu (2013). We adopt these MESA models for all evolutionary photoevaporative calculations; however, for old massive-planets we use an empirical radius-temperature relation as described in Section 2.2.1. In our calculations of lower-mass planets we ignore any possible additional radius inflation mechanism. If an inflation mechanism, such as Ohmic dissipation, operates in lower mass planets it could increase their radii above the values our models find (e.g. Pu & Valencia 2017), making photoevaporation more effective.

\[\text{https://exoplanetarchive.ipac.caltech.edu/}, \text{downloaded on 3rd August 2017}\]
Figure 1. Exoplanet radius-period (top panel) and mass-period (bottom panel) distribution. In the radius-period plot the circles are confirmed exoplanets, the squares are those with mass measurements, the crosses are possible eclipsing binaries identified by Cabrera et al. (2017) and the triangles are disintegrating rocky planets (Rappaport et al. 2012; Sanchis-Ojeda et al. 2015), where the transit radius corresponds to the size of the dusty cometary tail escaping the planet. In the bottom panel, the squares are $M_{\sin i}$ measurements, whereas the circles are mass measurements.

2.2.1 Empirical radius-temperature relation for massive planets

Hot Jupiters are known to have inflated radii (e.g. Baraffe et al. 2010; Enoch, Collier Cameron, & Horne 2012; Thorngren & Fortney 2018); the origin of this inflation remains unknown. This means that the mass-radius-period relation cannot be calculated a priori theoretically. We make use the observed exoplanets to obtain an empirical relation. The radius of “cold” gas giants is largely independent of mass, as a result the competition between the degeneracy pressure and Coulomb pressure; furthermore, hot Jupiter inflation is believed to be correlated best with the equilibrium temperature ($T_{\text{eq}}$, e.g. Laughlin et al. 2013; Thorngren & Fortney 2018; Sestovic et al. 2018). We therefore adopt the following empirical radius-temperature relation that best fits the observations (for planet mass $M_p \gtrsim 0.2 M_J$):

$$R_p/R_J = f \times \begin{cases} 0.8 \left( \frac{T_{\text{eq}}}{1100K} \right)^{0.7224} & \text{if } T_{\text{eq}} > 1100K \\ 0.8 & \text{if } T_{\text{eq}} \leq 1100K \end{cases}$$

(1)

The factor $f$ is chosen to be between 1 and 1.5, covering the spread in radius at a given equilibrium temperature. This relation is compared to the observed data in Figure 2 (red region). Since inflation may take some time to operate, such that tidally disrupting planets are not inflated when they arrive on their short period orbits, we also chose a non-inflated radius (grey region in Figure 2) that varies between 0.8 $R_J$ and 1.2 $R_J$.

3 PHOTOEVAPORATION

Exoplanets with H/He atmospheres (envelopes) can lose mass over time through photoevaporation. Proximity to their parent star results in a planet’s upper atmosphere being heated to temperatures of around $5,000 \text{ – } 10,000 \text{ K}$ by UV/X-ray photons, causing it to escape in a hydrodynamic wind. Over a planet’s lifetime this causes it to lose mass and typically shrink in radius. Since a star is only UV/X-ray bright for of order 100 Myr (Ribas et al. 2005; Jackson et al. 2012; Tu et al. 2015), photoevaporation predominately occurs at early times. Owen & Wu (2017) presented a schematic framework in which to consider the effect of evaporation: atmospheres with mass-loss timescale $t_\dot{m} \equiv M_{\text{env}}/\dot{m} \gtrsim 100$ Myr are stable to mass-loss, while those with $t_\dot{m} \lesssim 100$ Myr are unstable and evolve towards a lower-mass atmosphere. For those atmospheres that are unstable, if a lower-mass state with $t_\dot{m} \gtrsim 100$ Myr exists, then the atmosphere evaporates to the point where it becomes stable again. If no lower-mass atmosphere that is stable to evaporation exists then the planet’s atmosphere is completely stripped leaving behind a “naked”, or “stripped” core. The mass-loss timescale of a planet as a function of atmosphere/envelope mass fraction is schematically shown
in Figure 3 (following Owen & Wu 2017). The curve posses two turning points: The first occurs where the presence of atmosphere doubles the whole planetary radius (corresponding to a H/He atmosphere fraction of $X \sim 1\%$ relative to the core mass); the second occurs when the atmosphere mass is roughly equal to the core mass, at which point self-gravity compresses the atmosphere so as to maintain a a roughly constant planetary radius ($\sim P \sim 1.5 \mathrm{R}_J$ for H/He atmospheres); beyond this second turning point, the mass-loss time increases with the envelope mass. Thus, if the first turning point has $t_{\text{m}} \gtrsim 100$ Myr, while the second turning point has $t_{\text{m}} \lesssim 100$ Myr (as shown by the dotted and dashed lines in Figure 3), then there exists three minimally stable atmospheres (black circles in Figure 3): (a) a very low-mass one ($X \leq 0.01$) with the minimum envelope mass required to survive complete stripping, (b) an intermediate one (0.01 $\leq X \leq 1$) with a maximum atmosphere mass, and (c) a high-mass ($X \gtrsim 1$) one with a minimally stable atmosphere mass. If photoevaporation is the origin of either the upper or the lower boundary of the unoccupied region in the radius-period/mass-period plane, then it is the two more massive stable atmospheres (b & c) that designate the boundaries (the lowest mass stable atmosphere is the origin of the photoevaporation valley – Owen & Wu 2017). Specifically, the low-mass planet with the maximum atmosphere mass stable to photoevaporation (labelled b) defines the lower boundary, whereas the high-mass one with the minimum atmosphere mass (labelled c) defines the upper boundary. At small distance to the star, the mass-loss timescales of all planets decrease due to the increased high energy flux. Therefore the stability line, corresponding to a mass-loss timescale of 100 Myr, crosses the mass-loss curve at a higher point (represented by going from the red dashed line to the green dotted line in Figure 3). Thus, at shorter periods the lower boundary appears at lower envelope mass fractions (and hence smaller planetary radii), while the upper boundary due to photoevaporation appears at higher planet masses.

### 3.1 Upper boundary

For the upper boundary due to photoevaporation we take planets to be massive with an envelope mass fraction $X \gtrsim 1$, so the mass-loss timescales increases with increasing $X$ (see Figure 3). Before we show the results from numerical models, we can estimate the result by assuming that the planetary radii are roughly constant. The mass-loss time-scale $t_{\text{m}} = M_{\text{env}}/\dot{m}$ for massive planets with $M_{\text{env}} \sim M_p$ is

$$t_{\text{m}} \propto \frac{a^2 M_p^2}{R_{\text{HE}}^3},$$

where we have crudely used the “energy-limited” photoevaporation mass-loss rate (Lammer et al. 2003; Baraffe et al. 2004; $\dot{m} \propto R_{\text{HE}}^3/(a^2 M_p)$; with $L_{\text{HE}}$ the high-energy luminosity, $R_{\text{HE}}$ the radius of the base of the photo evaporative flow and $a$ the semi-major axis. Setting $t_{\text{m}} = 100$ Myr, we find that the planet mass on the upper boundary scales with orbital period ($P$) approximately as $M_p^\text{upper} \propto P^{-2/3}$. Looking at Figure 3 it is clear that the upper envelope empirically begins around a period of 3 days at $\sim 0.1 \mathrm{M}_J$, so the $P^{-2/3}$ scaling would imply that even at sub-day periods, planets with sub-jovian masses should be able to resist photoevaporation. This is inconsistent with the observed exoplanet distribution. This inference is confirmed by the full numerical calculations where we show that the initial and final masses of planets with $X > 1$ and a core mass of $10 M_\oplus$ are able to resist photoevaporation (see Figure 3). If photoevaporation were the origin of the upper boundary of the sub-jovian desert, the mass-period plane would be filled with sub-jovian mass planets at very short periods. This is clearly not the case, and we must look to another mechanism to explain the upper boundary (Section 4).

Our results are different from Kurokawa & Nakamoto (2014) who argued that photoevaporation of giant planets can explain the paucity of sub-jovian planets. There are two reasons for this: Firstly, Kurokawa & Nakamoto (2014) used a combination of energy-limited and recombination limited photoevaporation models. In the energy-limited regime they adopted a constant mass-loss efficiency of 25% following Kurokawa & Kaltenegger (2013), which tends to be a significant overestimate for giant planets (e.g. Owen & Jackson 2012), resulting in higher mass-loss rates. Secondly, in their analysis, the pressure at the base of the photoevaporative flow is fixed to be 1 nBar; such a choice tends to underestimate the pressure to which high-energy photons penetrate in sub-jovian planets. In the energy-limited model $\dot{m} \propto R_{\text{base}}^3$. Adopting a lower pressure at the base of the flow means adopting a lower pressure at the base of the flow means $R_{\text{base}}$ is larger than in reality and hence the mass-loss rate will be underestimated. The large mass-loss rates used by Kurokawa & Nakamoto (2014) led to mass-loss powered radius inflation, wherein the mass-loss timescale becomes shorter than the cooling time of the planet. When this happens $PdV$ work causes the giant planet’s envelope to expand, resulting in even larger mass-loss rates and greater envelope expansion.
(e.g. Baraffe et al. 2004, leading to a runaway. Kurokawa & Nakamoto 2014, indicated this evolutionary pathway would lead to Roche-lobe overflow and catastrophic mass-loss. In our models, due to the lower-mass loss rates, we find mass-loss powered radius inflation of giant planets does not occur and hence catastrophic run-away mass-loss does not happen for close-in hot Jupiters. This finding is in agreement with work by Ionov et al. (2018), who also showed massive planets could survive photoevaporation in the desert.

### 3.2 Lower boundary

Having shown that photoevaporation is incapable of explaining the upper boundary of the sub-Jovian desert in the mass-period plane, we now focus on the lower boundary in both the radius-period and mass-period planes. The schematic understanding of how photoevaporation creates a lower-boundary in Figure 3 indicates that these planets will be of low-mass and have envelope mass fractions in the range from 0.01 to 1.

In order to investigate the lower-boundary created by photoevaporation we numerically follow the long-term evolution of planets with envelope mass fractions initially less than unity as a function of period. We vary the planet's core mass and also the envelope metallicity, where we use the approximate scaling obtained by Owen & Jackson (2012) of \( m \propto Z^{-0.77} \) for the mass-loss rates, and we assume the bulk metallicity in the entire atmosphere is constant by scaling the bulk envelope metallicity by the same factor.

We then evolve this initial population of planets under the influence of photoevaporation for 5 billion years and for each core mass and atmosphere metallicity and find the largest and most massive planet that exists at a given period. The results in the radius-period plane for varying core masses between 10 and 13.75 M⊕, with solar metallicity are shown in Figure 5 and for atmospheric metallicity variations in the range 1 to 10 Z⊙, with a 10 M⊕ core are shown in Figure 6. It is clear from these figures that the shape of the lower boundary in the radius-period plane is well explained by photoevaporation. Comparing the model curves to the data we find the lower-boundary is well explained if the low-mass planet population has a maximum core mass slightly larger than \( \sim 10 \) M⊕, with the exact value depending on the atmospheric metallicity. Such a maximum core-mass agrees well with the observed gap in the radius distribution of small close-in planets (Fulton et al. 2017), located at 1.8 R⊕, corresponding to a stripped solid core of roughly 10 M⊕.

As well as investigating the lower boundary in the radius-period plane, we can compare the model boundaries
to the exoplanet data in the mass-period plane. This comparison is shown in Figure 7. The boundaries for various different core masses (dashed lines) and atmospheric metallicities (solid lines) are shown. The data for small exoplanets with measured masses is rather sparse and there is no clear sharp boundary in the mass-period plane. All we can say is that the theoretical boundary in the mass-period plane is consistent with the data. Finally, checking the few planets that are close to the theoretical radius-period boundary and have measured masses and radii we find that they all have masses in the range 10 – 25 M⊕, consistent with our expectation that these planets must have a core mass in the range of 10 – 15 M⊕.

4 TIDAL BOUNDARIES AND HIGH-ECCENTRICITY MIGRATION

Regardless of the formation channels of close-in planets, their current (circular) semi-major axes a must be larger than the critical tidal radius

\[ r_{\text{tide}} = \eta \left( \frac{M_p}{M_p} \right)^{1/3} R_p, \]

where \( \eta = 2 – 3 \), depending on the internal structure of the planet. For concreteness, we adopt \( \eta = 2.7 \) in the following based on simulations of giant planet disruption (Guillot et al. 2011).

In the high-eccentricity migration scenario, a planet is excited into a highly eccentric orbit due to gravitational interactions with other planets or with a distant stellar companion, followed by tidal dissipation in the planet which circularizes the orbit (e.g. Wu & Murray 2003; Fabrycky & Tremaine 2007; Nagasawa, Ida & Bessho 2008; Wu & Lithwick 2011; Beauge & Nesvorný 2012; Naoz et al. 2012; Petrovich 2015; Anderson, Storch & Lai 2016; Munoz, Lai & Liu 2016). Because tidal circularisation conserves (approximately) the orbital angular momentum, a planet with a pericenter distance \( r_p \) and eccentricity \( e \approx 1 \) will circularise at a “final” semi-major axis of \( a_f = (1 + e)r_p \simeq 2r_p \) (Ford & Rasio 2006). Thus, planets formed through high-eccentricity migration must satisfy \( a_f \geq 2r_{\text{tide}} \).

For simple power-law scaling \( R_p \propto M_p^\beta P^{-\alpha} \), the condition \( a_f \geq 2r_{\text{tide}} \) yields

\[ P \geq C_1 \left( \eta^3 M_p^{3\beta-1} \right)^{1/2 - 3\alpha}, \]  

or

\[ P \geq C_2 \left( \eta^3 R_p^{3\beta-1} \right)^{1/2 + \alpha}, \]

where \( C_1, C_2 \) are proportional constants. In reality, \( R_p \) does not have a simple power-law dependence on \( M_p \) and \( P \) (e.g., For gas giants, the radius depends weakly on mass but may depend on the period, while for super-earths there is no unique mass-radius relationship as \( R_p \) depends on the envelope fraction). Therefore, for massive planets we use the empirical radius-temperature relation discussed in Section 2.2.1 and for the small planets we use MESA to calculate the mass-radius relation for different core masses by setting the age of the planets to 1 Gyr (our results are fairly insensitive to this choice).

Note that high-eccentricity migration can only form planets with sufficiently short orbital periods. In order to migrate efficiently, the planet, starting from an initial semi-major axis \( a_0 \sim 1 \) au, must be pushed to a sufficiently large eccentricity (or sufficiently small pericenter distance \( r_p \)) for tidal circularisation to operate. A crude estimate for the orbital decay rate in Lidov-Kozai migration is (see Eq. 32 of Anderson et al. 2016, or Eq. 8 of Munoz et al. 2016)

\[ \frac{\dot{a}}{a_{\text{tide,LK}}} \simeq 2.8k_2p(\Delta t_{\text{lag}}) \frac{G M_p^2}{M_p} \frac{R_p^5}{a_0^2}, \]

where \( k_2p \) is the Love number of planet and \( (\Delta t_{\text{lag}}) \) is the tidal lag time (in the weak tidal friction theory). Requiring \( |\dot{a}/a_{\text{tide,LK}}| \gtrsim \tau_{\text{lag}}^{-1} \), we find that the final (“circularised”) semi-major axis \( a_f \simeq 2r_p \) must satisfy

\[ a_f \lesssim 0.05 \text{au} \left( \frac{\tau_{\text{lag}}}{\text{Gyr}} \right)^{1/7} \left( \frac{Q_p'}{10^8} \right)^{-1/7} \left( \frac{M_p}{M_\odot} \right)^{2/7} \times \left( \frac{a_0}{\text{au}} \right)^{-1/7} \left( \frac{M_p}{M_J} \right)^{-1/7} \left( \frac{R_p}{R_J} \right)^{5/7}, \]  

where \( Q_p' = Q_p/k_2p \), and we have defined the tidal quality factor (at the tidal period of 1 day) via \( Q_p^{-1} \equiv (2\pi/\text{day})(\Delta t_{\text{lag}})^{-1} \).

The dashed lines represent the boundaries obtained from the runs with different core masses and are the same as the coloured lines shown in Figure 3, the solid lines represent the variation from the 10 M⊕ core due to enhanced metallicities in the planet’s atmosphere and are the same as the lines shown in Figure 7.

4.1 Lower boundary

Figure 8 shows the tidal disruption boundaries for low-mass planets (\( M_p < 0.15M_J \)) in both the radius-period (top panel) and mass-period (bottom panel) planes. It is clear that while
The sub-Jovian desert

Figure 8. Tidal disruption boundary ($a = r_{\text{tid}}$) for planets with mass $< 0.15 M_J$. Each line represents a different core mass with 5 (solid), 10 (dashed) and 15 $M_J$ (dotted) cores shown. In these plots the points represent observed planets and are identical to those in Figure 1.

the observed planets do indeed satisfy the criterion $a > r_{\text{tid}}$, the tidal boundary does not match the paucity of the data.

In Figure 9 we show the boundaries for planets that have undergone high-eccentricity migration (i.e., the circularized semi-major axis $a_F = 2r_{\text{tid}}$). We also plot the “circularisation efficiency boundary” (Equation 7 for $Q'_p = 10^5$), indicating that planets that have experienced Lidov-Kozai oscillations must have smaller periods than this boundary in order to circularise on a Gyr or shorter time-scale. The thick solid cyan line shows the circularisation efficiency constraint for $Q'_p = 100$, appropriate for a primarily solid composition, and thus may only be applicable for small, low-mass H/He envelopes.

The two panels in Figure 9 show that high-eccentricity migration can explain parts of the lower boundary of the sub-Jovian desert. However, the range of periods in which planets can reside having formed through a high-eccentricity migration mechanism like Lidov-Kozai oscillations is very narrow and very few planets lie between the tidal disruption boundary (magenta lines) and the circulation efficiency boundary (black lines). Unlike the photoevaporation model these boundaries in the radius-period plane are somewhat insensitive to core mass, with planets with core masses of $\sim 5 M_J$ allowable close to the boundary. Therefore, the presence of planets with masses $\lesssim 10 M_J$ sitting in-between the magenta and black dashed lines would argue that they arrived through high-eccentricity migration. Since high-eccentricity migration...
migration is expected to operate on a longer timescale than the 100 Myr timescale of photoevaporation, late-time mass-loss due to photoevaporation is likely to be minimal. Therefore we do not expect the high-eccentricity migration lower boundary to be affected by evolution after the planet has circularised. We note that the population of small \((R < 2 \text{ R}_\oplus)\) planets at sub-day periods could clearly not have been produced by high-energy migration and the bulk of the population of super-earths mini-neptunes could not have migrated in via Lidov-Kozai oscillations. Therefore, we conclude that while photoevaporation is likely to have sculpted the low-mass planet population creating the lower-boundary it could be polluted by late time high-eccentricity migration of Neptunes/sub-Saturn mass planets.

### 4.2 Upper Boundary

For giant planets, we use the empirical planet radius relation in Equation 7. To convert the equilibrium temperature to orbital period we fix the stellar mass to be 1 M\(_\odot\), stellar radius to be 1 R\(_\odot\) and stellar effective temperature to 5780 K.

In Figure 10 we show both the tidal boundary \((a = r_{\text{ tide}})\) dotted line) and the minimum circularisation period (corresponding to \(a = 2r_{\text{ tide}}\); magenta region) and the maximum period for circulations through Lidov-Kozai oscillations on shorter than Gyr timescales (Equation 7 with \(Q'_t = 10^7\); dashed line) for massive planets. The points represent the observed planets and are identical to those in the lower-panel of Figure 1. For clarity, we plot the tidal disruption boundary for its minimum value, while for tidal circularisation we show it as a band, accounting for the spread in the observed radii of giant planets (see section 2.2.1).

Figure 10. The mass-period plane showing the tidal disruption line \((a = r_{\text{ tide}})\;\text{dotted line}) and the minimum circularisation period (corresponding to \(a = 2r_{\text{ tide}}\); magenta region) and the maximum period for circulations through Lidov-Kozai oscillations on shorter than Gyr timescales (Equation 7 with \(Q'_t = 10^7\); dashed line) for massive planets. The points represent the observed planets and are identical to those in the lower-panel of Figure 1. For clarity, we plot the tidal disruption boundary for its minimum value, while for tidal circularisation we show it as a band, accounting for the spread in the observed radii of giant planets (see section 2.2.1).

\[
\frac{a}{a} = -\frac{9}{2} \left( \frac{G}{M_\star} \right)^{1/2} \frac{R_\text{ tide}}{Q'_t} a^{-13/2},
\]

where \(Q'_t\) is the reduced tidal quality factor of the star. We integrate Equation 8 over a fixed time interval \(\Delta t\). Since neither \(Q'_t\) or \(\Delta t\) are known, we constrain the ratio \(\Delta t/Q'_t\) by requiring that the planets in Figure 10 that reside between the circularisation limit and the tidal limit reached their current orbits by tidal decay. With a choice of \(\Delta t/Q'_t\) of 160 years (corresponding to \(Q'_t \sim 10^7\) for \(\Delta t \sim 1\) Gyr), we find the upper boundary of the sub-jovian desert can be well explained.

In Figure 11 we show the resulting change to the upper boundary in the mass-period plane that results from tidal circularisation at twice the tidal destruction radius, followed by tidal decay towards the star (magenta region). We also include the boundary (the blue region) that would arise if the planets did not become inflated until they had fully circularised; in this case we find that the best-fit \(\Delta t/Q'_t\) is 20 years.

In addition, we plot a constant tidal decay time \((\sim 0.1\) Gyr) boundary in Figure 11 shown as the dot-dashed line. This boundary arises as one is unlikely to observe planets to the left of this line as they would be currently undergoing extremely rapid decay into the star. Two planets stand out as appearing to be inconsistent with the high-eccentricity boundary: Kepler-41b (red dot) and WASP-52b (black dot). Kepler-41b is consistent within its 1 \(\sigma\) mass error bar. WASP-52b is a \(\sim 0.5\) M\(_\text{Jup}\) mass planet with a radius of 1.27 \(R_\text{Jup}\) (Hebrard et al. 2013), indicating it is not an outlier in terms of giant planet inflation. WASP-52b does not appear to have any unusually distinguishing features other than a slightly unusual optical transmission spectrum (Louden et al. 2017). Either WASP-52b did not reach its present location by high-eccentricity migration, or it did not become inflated until it had finished circularising. Both these cases would make WASP-52b an interesting outlier in the context of hot Jupiter formation.

As we have fit for the radius-equilibrium temperature relation in Section 2.2.1, our model reproduces the radius-period upper boundary. This match is obviously by construction and not a test.

Our tidal circularisation boundaries are qualitatively similar to those obtained by Matsakos & Königl (2010) however, we have adopted a more realistic mass-radius-separation relation. This difference results in our model pre-
ferring a higher value of $Q'$ ($\sim 10^7$ rather than $10^6$); as $Q'$ is not constrained theoretically or observationally yet within this range, this difference is not important. Additionally, we have shown (Figure 9) that only a small region of the lower-mass planets with H/He envelopes could have arrived by high-eccentricity migration, in agreement with population studies of photoevaporation (Owen & Wu 2017; Wu 2018).

5 IMPLICATIONS FOR THE ORIGIN OF CLOSE-IN PLANETS

Understanding the mass/radius vs period distribution of exoplanets can shed light on the origins of different exoplanet populations. The presence of the “evaporation-valley” in small, close-in exoplanets (Fulton et al. 2017; Owen & Wu 2017; Van Eylen et al. 2017) indicates that the majority of these planets have formed inside the snow-line and arrived at their current locations before, or soon after the gas disc dispersed. These close-in planets are then sculpted by photoevaporation, producing the lower boundaries in the radius-period/mass-period distributions.

However, it is clear that photoevaporation alone cannot explain both boundaries of the sub-jovian desert, as $M_p \gtrsim 0.5 \, M_J$ planets are able to resist photoevaporation even at extremely short orbital periods. If the formation process for close-in low-mass planets (that are consistent with the evaporation valley and the lower boundary of the sub-jovian desert) produced a continuum of envelope mass fractions $X > 1$, then we should find the planets with intermediate masses at short periods (i.e. 100 $M_J$ planets in 1 day orbits). Clearly, this is not the case and therefore, whatever the mechanism that produced the bulk of the low-mass, close-in planet population, it was unable to produce planets with envelope mass fractions $\gtrsim 1$.

For the population of more massive planets ($M_p \gtrsim 0.2 \, M_J$) we find that their distribution in the mass-period plane is consistent with high-eccentricity migration, with more massive planets surviving closer to their host stars. At masses above $\sim 1 \, M_J$, tidal decay allows the planets to reach shorter orbital periods after orbital circularisation. By comparing with the data we require the effective stellar tidal quality factor to be of order $10^7$, assuming high-eccentricity migration operates on a Gyr time-scale. This means that the majority of more massive planets, with envelope mass fractions $\gtrsim 1$, formed at long periods and then were delivered to their current short-period orbits. The shape of our upper boundary, with tidal decay becoming important above $\sim 1 \, M_J$, may explain the lack of intermediate-mass planets at high irradiation levels, as noted by the recent studies of hot-Jupiter inflation (Thorngren & Fortney 2018; Sestovic et al. 2018). All giant planets are consistent with this scenario except WASP-52b. Therefore, we conclude that the bulk of close-in giant planets and close-in low-mass planets must have formed through distinctly different channels at different locations in their nascent protoplanetary discs and arrived at the short-period orbits on very different time-scales.

Our results indicate that in-situ formation of giant planets either does not happen, or is extremely rare. Furthermore, it seems unlikely that migration of giant-planets through their discs can explain the shape of the upper boundary (particularly the fact that more massive planets can reach shorter periods) as type-II migration is either mass-independent (when the disc mass exceeds the planet mass), or is slower for more massive planets (when the planet mass exceeds the disc mass, Syer & Clarke 1995). It is of course possible that the planets with masses above $1 \, M_J$, for which we have invoked tidal decay to explain their current orbits, could have migrated through discs. Disc migration of such massive giant planets does occur in some planet population synthesis studies (e.g. Ida & Lin 2008; Bitsch, Lambrechts, & Johansen 2015). While high-eccentricity migration still suffers from several unsolved theoretical problems, it appears to be the dominant process for generating short-period giant planets (see Dawson & Johnson 2018 for a recent review).

We note that both photoevaporation and high-eccentricity migration give similar lower-boundaries in the mass-period and radius-period planes. The only difference is that high-eccentricity migration can produce lower mass planets ($\lesssim 5 \, M_J$) near the radius-period boundary, whereas photoevaporation requires them to be more massive ($\sim 10 \, M_J$). However, low-mass planets can only be produced by high-eccentricity migration followed by tidal circularisation in a very narrow range of parameter space, in which very few observed “hot neptunes” reside. The current data is too sparse to test this in any detail. Dong et al. (2017) suggest that these “hot neptunes” are mostly singles, and therefore favours high-eccentricity migration. The metallicity dependence of the boundary, with larger mini-neptunes being common close to their host stars at higher stellar metallicities (Dong et al. 2017; Petigura et al. 2018), is also consistent with this suggestion. Due to the narrow range of parameters in which high-eccentricity migration can produce hot
neptunes, such metallicity preference should be confined to orbital periods less than a few days. Owen & Murray-Clay (2018) show that the uptick in stellar metallicity preference begins at a period of 20 days, and thus is more consistent with a photoevaporative origin.

We can suggest several possible tests of our scenario. The close-in giant planet frequency should be lower around younger stars, as they don’t reach their current orbits until late-times. Also, the lower boundary in the radius-period plane should appear at larger radii around younger stars as the planets are still losing mass. Alternatively, if a significant fraction of lower-mass planets near the radius-period boundary should not evolve with time; the boundary should be populated with planets with masses \( \lesssim 10 M_\oplus \), and these planets should not have nearby companions and should show evidence for long-period companions. Finally, if tracing back in time the evolution of H/He hosting planets near the boundary, accounting for photoevaporative migration, the planetary radius at the boundary should not evolve with time; the boundary should be populated with planets with masses \( \lesssim 10 M_\oplus \), and these planets should not have nearby companions and should show evidence for long-period companions. Finally, if tracing back in time the evolution of H/He hosting planets near the boundary, accounting for photoevaporative mass-loss (as done for Kepler-36 b/c in Owen & Morton 2010) requires an unphysical initial condition (e.g. a planet with an initially large, high-entropy H/He atmosphere that would, in reality, be unbound from the core) then one knows that planet could not have been photoevaporated to its current state.

ACKNOWLEDGEMENTS

We are grateful to the referee for comments which improved the manuscript. JEO is supported by a Royal Society University Research Fellowship. DL is supported by NASA grant NNX14AP31G and NSF grant AST1715246. JEO is grateful to participants of the 2016 Kavli Summer Program in Astrophysics held at UC Santa Cruz where questions about photoevaporation’s efficacy in generating the sub-jovian desert were raised. This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the auspices of the NASA Exoplanet Archive.

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