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EMERGING TRENDS IN A PERIOD–RADIUS DISTRIBUTION OF CLOSE-IN PLANETS

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ABSTRACT

We analyze the distribution of extrasolar planets (both confirmed and *Kepler* candidates) according to their orbital periods P and planetary radii R. Among confirmed planets, we find compelling evidence for a paucity of bodies with $3\ R_\oplus < R < 10\ R_\oplus$, where $R_\oplus$ is Earth's radius and $P < 2$–3 days. We have christened this region a *sub-Jovian Pampas*. The same trend is detected in multiplanet *Kepler* candidates. Although approximately 16 *Kepler* single-planet candidates inhabit this Pampas, at least 7 are probable false positives (FPs). This last number could be significantly higher if the ratio of FPs is higher than 10%, as suggested by recent studies. In a second part of the paper we analyze the distribution of planets in the (P, R) plane according to stellar metallicities. We find two interesting trends: (1) a lack of small planets ($R < 4\ R_\oplus$) with orbital periods $P < 5$ days in metal-poor stars and (2) a paucity of sub-Jovian planets ($4\ R_\oplus < R < 8\ R_\oplus$) with $P < 100$ days, also around metal-poor stars. Although all these trends are preliminary, they appear statistically significant and deserve further scrutiny. If confirmed, they could represent important constraints on theories of planetary formation and dynamical evolution.

Key words: planets and satellites: general – stars: abundances

Online-only material: color figures

1. INTRODUCTION

Close-in (or hot) planets, usually defined as those having semimajor axes $a < 0.1$ AU (or orbital periods $P < 10$ days), are the easiest to detect, both with radial velocity (RV) surveys and transits. Almost half of the confirmed planets currently known correspond to this population, although this proportion is certainly affected by observational bias. It is believed that close-in planets cannot have been formed in situ (e.g., Lin et al. 1996), and thus constitute an interesting evidence for orbital migration and dynamical evolution of extrasolar planetary systems.

While most of the exoplanets detected by Doppler techniques correspond to giant planets (typically, masses $m \geqslant 0.3\, m_{\rm Jup}$), the recent discoveries from *Kepler* have been dominated by much smaller planets, usually in the super-Earth and Neptune mass range. Although this may point to the fact that smaller planetary bodies are more numerous (e.g., Mayor et al. 2011; Howard et al. 2010, 2012), the exact statistics also depends on metallicities of the host stars (e.g., Fischer & Valenti 2005; Santos et al. 2011).

The distribution of planets in a planetary radius (R) versus orbital period (P) plane provides important information about planetary formation and migration in different planet-size regimes (e.g., Benítez-Llambay et al. 2011; Latham et al. 2011; Youdin 2011; Hasegawa & Pudritz 2012). Also, planetary occurrence in the (P, R) plane for different stellar metallicities and effective temperatures $T_{\rm eff}$ may lead to insights on how these parameters affect both planetary formation and orbital migration. For example, there is indication that sub-Jovian planets may be found in a wider range of metallicities than giant planets (Buchhave et al. 2012), and that giant planet occurrence increases with $T_{\rm eff}$ and stellar mass (Johnson et al. 2010; Howard et al. 2012).

In this paper we perform a detailed analysis of planets in the (P, R) plane, including public data from both confirmed planets and *Kepler* planetary candidates. We restrict our analysis to planets with orbital periods $P < 50$ days and host stars with masses $m_* > 0.5\, m_\oplus$. Our goal is to search for possible (statistically significant) trends in the (P, R) plane and discuss possible explanations for these trends. In Section 2 we analyze the distribution of close-in planets in the (P, R) plane and point out the possible existence of a sub-Jovian desert for orbital periods lower than ∼2–3 days. In Section 3 we discuss several new trends in the (P, R) distribution of planets according to the stellar metallicity. For planets without detected transits we extend our analysis to the plane of orbital period versus minimum planetary mass (i.e., (P, m) diagram). Discussions and possible dynamical interpretations of the detected trends close the paper in Section 4.

2. THE DISTRIBUTION OF SUB-JOVIAN PLANETS

2.1. A Sub-Jovian Desert?

Figure 1 shows the distribution of orbital periods of all confirmed planets (as of 2012 July) with $P < 50$ days, totaling 287. The left plot shows P as a function of the mass, while the one on the right shows the corresponding distribution in terms of the planetary radius R. These two data sets are not identical because some planets have no detected transits, and thus no information is known of their radii.

We can separate the planets, according to their mass, roughly into three groups: Jovian planets ($m \geqslant 1\, m_{\rm Jup}$), Neptunes or sub-Jovian planets ($0.03\, m_{\rm Jup} \leqslant m < 1\, m_{\rm Jup}$), and super-Earths ($m < 0.03\, m_{\rm Jup}$). This division is arbitrary, but it can be useful to highlight different formation mechanisms of different populations. In terms of the physical radii, these groups can also roughly be defined by the relations: $R \geqslant 11\ R_\oplus$ for Jovian planets, $3\ R_\oplus \leqslant R < 11\ R_\oplus$ for Neptunes and sub-Jovian planets, and $R < 3\ R_\oplus$ for super-Earths. However, the observed diversity in planetary densities implies that there is no unique relationship between radius and mass, so the above relationship is only illustrative. Also keep in mind that in most cases planetary masses estimated from Doppler surveys are only minimum bounds to actual values, because of the (generally)

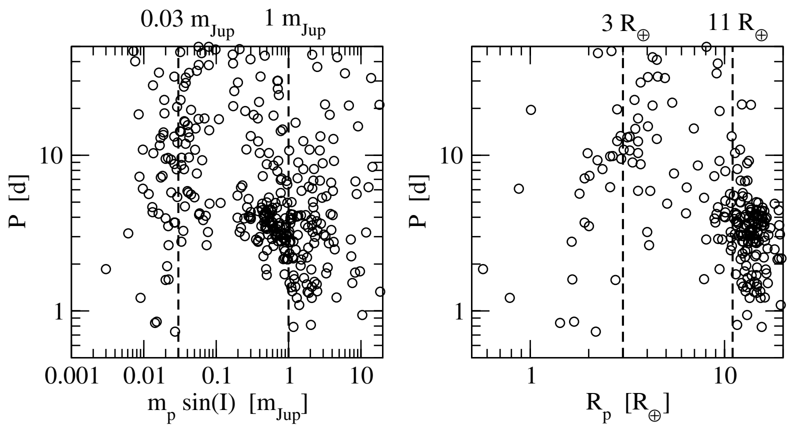

Figure 1. Distribution of orbital periods with planet mass (left) and radius (right) for a total of 287 confirmed planets with orbital periods $P < 50$ days.

unknown inclination of the orbital plane with respect to the observer's line of sight.

Even with these reservations in mind, Figure 1 shows an apparent absence of sub-Jovian planets with orbital periods smaller than $P \sim 3$ days. Possibly the first reference to a possible *sub-Jovian desert* was made by Szabo & Kiss (2011), although most of the super-Earths then detected belonged to small mass stars. Benítez-Llambay et al. (2011) corrected that distribution by normalizing the semimajor axis by stellar mass and radius; with the exception of CoRoT-7b, the other exoplanet population seemed to have a distribution more in accordance with a *step* function. Specifically, the orbital periods of close-in planets with $m > m_{\rm Jup}$ appeared to be restricted to periods $P > 1$ day, while smaller masses seemed to be detected only down to $P \sim 3$ days. This trend seems compatible with the existence of an inner cavity in the protoplanetary disk acting as a planetary trap for type I migration, plus a long-term evolution due to tidal effects after the gas disk dispersal (Benítez-Llambay et al. 2011).

Over the past year, however, as the population of small mass increased dramatically (especially due to *Kepler*), a significant population of small super-Earth planets has been detected around solar-type stars with lower orbital periods, also down to $P \sim 1$ day or even lower. Nevertheless, the absence of very hot sub-Jovian planets is still maintained and today, with 287 confirmed planets, the existence of this unpopulated region appears very prominent, especially in the (P, m) plane (Figure 1, left).

Although observational bias cannot be ruled out, it seems unlikely. While planetary detection via Doppler techniques favors large masses, several planets have been found in the sub-Jovian mass range with longer orbital periods. Moreover, in principle *Kepler* should have little problem in detecting a planet within this proposed sub-Jovian desert. An estimate (Koch et al. 2004) shows that planets in this region should have a signal-to-noise value between 400 and 1600 (assuming a solar-type star, observational time of one year, and an impact parameter $b = 0.5$), much higher than most of the confirmed *Kepler* planets.

Population synthesis models (e.g., Ida & Lin 2004; Mordasini et al. 2009, 2012) predict a paucity of Neptune-size planets relatively close to the star as a result of the interplay between planetary formation timescales and different migration regimes (type I and type II). However, these predictions have not been validated (e.g., Howard et al. 2012). The desert proposed by Szabo and Kiss is too sharply defined in the mass range, includes masses almost up to 1 $m_{\rm Jup}$, and is restricted to very small orbital periods.

As of 2012 July, there are more than 2300 *Kepler* candidate planets that have not been confirmed nor validated. We tested whether the distribution of these candidates in the (P, R) plane also shows the sub-Jovian desert or introduces a smoother distribution. However, we must keep in mind that among *Kepler* candidates, there are bound to be a number of false positives (FPs), whose number is still a matter of debate. Lissauer et al. (2012) argued that although FPs may be more common among *Kepler* Objects of Interest (KOIs) with only a single transit signal, among targets displaying multiple-planet transits the fraction of real systems could be as large as 95%.

The left plot in Figure 2 shows the distribution of these candidate systems (green circles), once again in the (P, R) plane. For comparison, the confirmed planets, in great majority coming from observations other than *Kepler*, are shown in black. *Kepler* multiple candidates tend to be smaller and contain almost no hot Jupiters (HJs). On the other hand, a significant number of super-Earth candidates are seen, some of them in systems with up to six planets. However, the sub-Jovian desert is still apparent in this data. For $P < 3$ days, there is a large number of HJs from RV surveys and a large number of super-Earths (and Neptunes) from *Kepler*, but almost no planets with radii between 3 and 11 $R_\oplus$.

In order to analyze whether this lack of planets is statistically significant, we performed a very simple Monte Carlo test. We counted the number of detected bodies (including both confirmed planets and multiple systems candidates) with $R \in [3, 10]$ $R_\oplus$ and $P \in [0.5, P_{\rm max}]$ days, $P_{\rm max}$ being an upper limit which was varied in successive trials. For each value of $P_{\rm max}$ we then generated a series of 10^6 fictitious populations with the same number of data points within the same intervals of P and R, and counted what percentage of them included no values within the proposed desert. We varied $P_{\rm max}$ between 10 and 50 days, and considered uniform distributions in (P, R) as well as in $(\log P, \log R)$. Depending on the value of $P_{\rm max}$ and the chosen distribution function, we found that the probability of reproducing the desert was at most 2%, although in most cases much smaller than 1%. Although this test is far from conclusive, its results are suggestive.

We then proceeded to do a different and slightly more elaborate statistical test. First, we searched for a region around the suspected desert with a population of detected planets as uniform and homogeneous as possible. Although our first choice was to analyze the distribution in planetary radius around

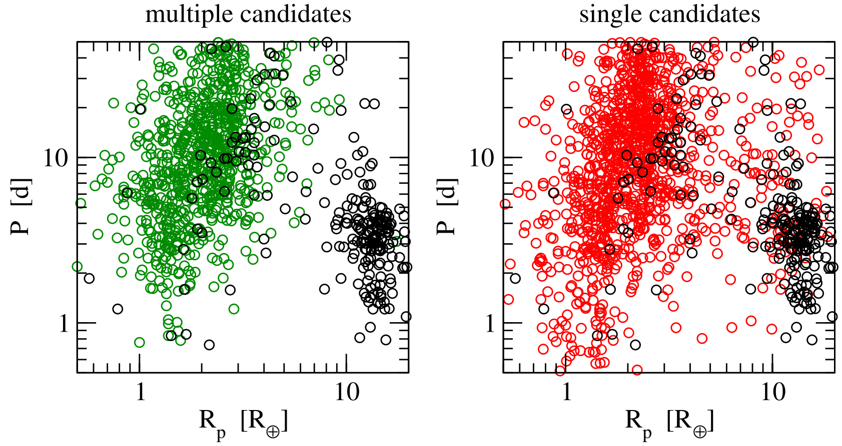

Figure 2. Distribution of orbital periods with planet radius, for all confirmed planets (black, $N = 232$) and *Kepler* candidates (green and red), separated according to multiple *Kepler* systems (left, $N = 784$) and single *Kepler* candidates (right, $N = 1114$).

(A color version of this figure is available in the online journal.)

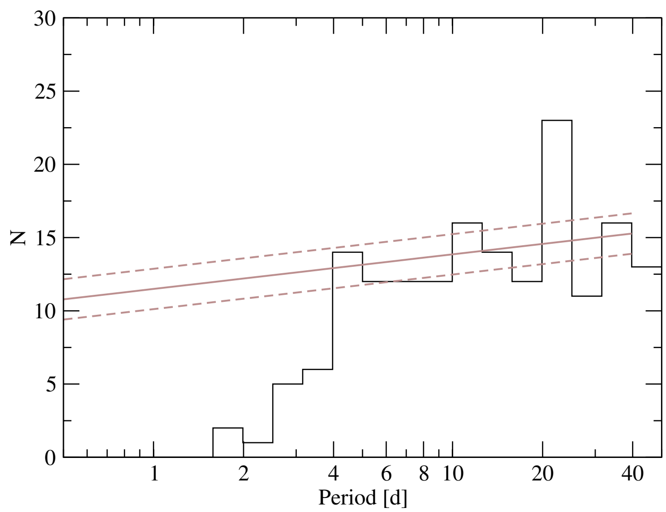

Figure 3. Distribution of medium-size planets ($R \in [3, 10]$ $R_\oplus$) as a function of their orbital period, including both confirmed and *Kepler* multiplanet candidates. The gray continuous line shows a linear fit in $\log(P)$ obtained considering only those planets with $P > 4$ days. Dashed lines show the 1σ values.

(A color version of this figure is available in the online journal.)

$P \sim 3$ days, we noted that both the stellar populations and detection techniques that dominate each side of the desert are different (*Kepler* for smaller planets and RV for Jovian masses), and therefore it would not be correct to construct a single fitted distribution function for both sub-populations. In consequence, once again we chose the distribution of observed planets according to orbital period, delimited in values of R within $R \in [3, 10]$ $R_\oplus$.

We then binned the observed population of planets in the interval $P \in [0.5, 50]$ days and fitted the data using a polynomial distribution. We found that the resulting functional fit was practically linear in $\log P$, with coefficients that were very robust with respect to the bin size. Together with the coefficients of the fit, we also estimated their uncertainties σ_i. Finally, we projected this fitted distribution function to the region of the proposed desert (i.e., $P < 3$ days) and compared it with the observed distribution. We found that the difference between them is of excess of 7σ, where σ is an estimation of the variance of the fit in this region. An example is shown in Figure 3. Again, the observed lack of planets close to the star does not appear consistent with the distribution found for larger orbital periods.

2.2. Problematic Cases and Possible FPs

Although the distribution of *Kepler* multiplanet candidates preserves the alleged desert, once the single-planet candidates are introduced, the distribution for $P < 3$ days becomes more fuzzy (red circles in Figure 2 (right)). In particular, the sub-Jovian region with $P < 3$ days now appears populated with around 16 planetary candidates. The question therefore arises: does this mean that the sub-Jovian desert is not completely void of planets, or are these "problematic" candidates FPs?

Among single candidates, the percentage of FPs is expected to be higher than for multiple-candidate systems. Morton & Johnson (2011) estimated FPs of the order of 10%, while Borucki et al. (2011) mentioned values as large as 20% for rank 2 KOIs, and even 40% for ranks 3 and 4. More recently, Santerne et al. (2012) performed RV observations on a sample of 46 *Kepler* candidates with orbital periods below 25 days, and concluded that as much as 35% of the single-planet candidates could be FPs. Colón et al. (2012) have proposed an even larger FP fraction, close to 50%, especially for small orbital periods.

Recently, Bonomo et al. (2012) compared the number of planets with $2\ R_\oplus \leqslant R \leqslant 4\ R_\oplus$ detected by *CoRoT* with the number of planets+candidates proposed from *Kepler* data. They pointed out that, according to the planetary occurrence ratio proposed by Howard et al. (2012), *CoRoT* should have detected a much larger number of hot Neptunes than actually found. Although the discrepancy could be due to the different stellar populations observed by both missions, it could also be indicative of an underestimation of the FP probability assumed by Howard et al. (2012).

Given these results, it is perhaps possible that the ∼16 candidates within the proposed desert are in fact FPs. We discuss this possibility in more detail below.

Two of our problematic cases (KOI 64.01 and KOI 102.01) were mentioned by Borucki et al. (2011) as possible FPs. Ofir & Dreizler (2012) presented an independent planet search in the *Kepler* database, using a modified version of the SARS pipeline (Ofir et al. 2010) developed for *CoRoT*. The treatment of the data was slightly different from the software used by the *Kepler* team. The authors rejected 11 KOIs as eclipsing binaries (EBs) based on close inspection of the light curves. Among these, another of our problematic cases (KOI 1459.01) appears, which is identified as an EB. Last of all, Colón et al. (2012) perform multi-color transit photometry on four *Kepler*

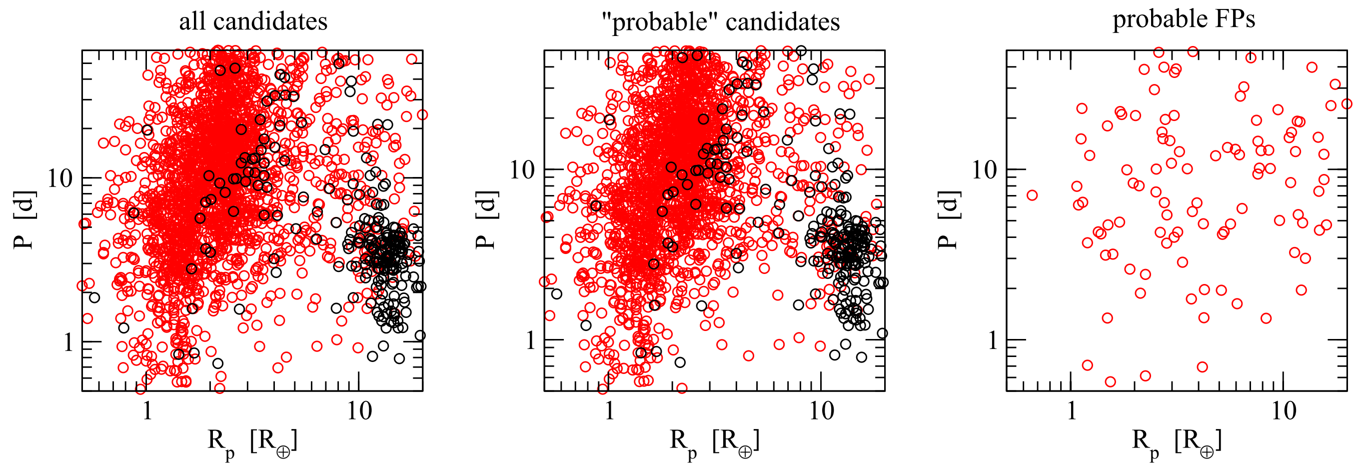

Figure 4. Distribution in the (P, R) plane of all confirmed planets (black) and *Kepler* candidates (red). Plots show all planetary candidates (left), "probable" planets (center), and probable false positives (right). See the text for details.

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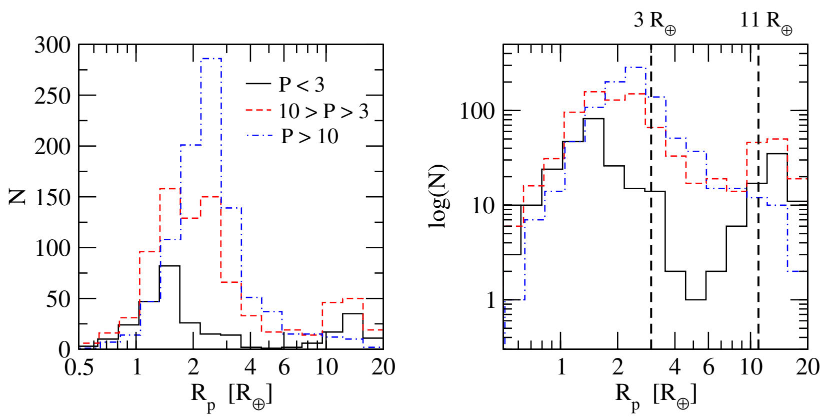

Figure 5. Distribution of planets according to radii for three intervals of orbital period ($P < 3$ days in black, 3 days $\leqslant P < 10$ days in red, and $P \geqslant 10$ days in blue). Plot on the right shows the same data as the one on the left, but with the number of bodies in log scale.

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candidates, and find that two are indeed FPs. KOI 1187.01, another of our problematic cases, is among them.

From these sources we can construct a data set of questionable candidates, subtract them from the planetary candidate list, and thus define a more "probable" list of planetary candidates. Figure 4 shows the change in the (P, R) distribution of *Kepler* candidates when these questionable cases are eliminated. The overall shape of the distribution is maintained, but now the number of planets in the proposed desert has decreased significantly, from 16 to 9. Their KOI numbers are: 356.01, 439.01, 506.01, 732.01, 823.01,1285.01, 1812.01, 1988.01, and 2276.01. It will be interesting to see whether these candidates survive future scrutiny.

Finally, the right-hand frame of Figure 4 shows the distribution of the proposed FPs. Their distribution in the (P, R) plane is fairly uniform and contrasts with both previous plots. Here we have included 158 proposed FPs, which represent less than 7% of all planetary candidates and 11% of single-planet candidates. If the ratio of FPs is much higher, as suggested by studies mentioned earlier in this section, then it is possible that most or even all of the problematic cases within the sub-Jovian desert may actually be FPs.

2.3. A Sub-Jovian Pampas

Even if some of these problematic cases are confirmed as actual planets, the sub-Jovian region with orbital periods below ~2–3 days still appears significantly underpopulated. In such a case, it would be more appropriate to refer to this region as a *sub-Jovian Pampas*, as characterized by a significantly lower planetary occurrence with respect to the surrounding regions.

Figure 5 shows the distribution of confirmed planets and *Kepler* candidates according to planetary radii, for three intervals of orbital period (values are specified in the upper right-hand corner of the left plot). For $P > 10$ days, the distribution shows a maximum around $R \sim 2$–$3\ R_\oplus$ and sharp decrease in planetary occurrence for both larger and smaller radii. This distribution is not corrected with respect to observational bias, so the real distribution of planets must be significantly different, especially for $R \sim R_\oplus$ (Mayor et al. 2011; Howard et al. 2012).

The observed distribution for lower orbital periods ($P \in [3, 10]$ days) appears bimodal, with a global maximum near $2\ R_\oplus$ and a second (local) maximum for Jovian masses. While some HJs may have reached this orbital distance through gas disk-driven orbital migration, at least some of them are believed to be the consequence of tidal circularization from high-eccentricity orbits caused by Kozai-capture (e.g., Naoz et al. 2012) or planetary scattering (Nagasawa et al. 2008; Beaugé & Nesvorný 2012). The bimodality of the planetary distribution for $3 \leqslant P < 10$ days in Figure 5 could be because this plot combines discoveries from two different sources (RV surveys and *Kepler*) which have different sensitivities and focus on different stellar populations. However, it could also be real, indicating that tidal capture is not as effective for sub-Jovian planets.

For $P < 3$ days, the bimodality is even more pronounced, and the sub-Jovian region for these short periods appears severely underpopulated. Again, some (or most) of the HJs could have been tidally captured, while most of the super-Earths could have been driven very close to the star by disk–planet interactions. It is not clear why neither appears to have been effective for sub-Jovian bodies.

Youdin (2011) presented an analysis of the distribution of *Kepler* candidates in the (P, R) plane, fitting different power laws for four sub-samples: planets smaller or larger than 3 $R_\oplus$, and orbital periods lower or higher than $P = 7$ days. He found significant differences in the size distribution of planets for $P < 7$ days and $P > 7$ days. This result is closely related to the paucity of sub-Jovian planets discussed here. However, since he did not include data other than *Kepler*'s, and did not eliminate possible FPs, none of his distributions exhibited bi-modality.

3. DISTRIBUTION OF CLOSE-IN PLANETS WITH STELLAR METALLICITY

The paucity of HJs in detections by *Kepler*, with respect to RV surveys, is believed to be due to low metallicity in most of the KIC. Nevertheless, the jury is still out with respect to small masses. Previous spectroscopic analysis of host stars with planets has been limited to those detected with RV surveys (e.g., Santos et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010; Sousa et al. 2011), and thus mainly to giant planets. These results indicate that Jupiter-size bodies are more likely to be found around metal-rich stars, at least in what concerns the population of planets in close-in orbits. This tendency is not so clear for Neptune-size planets (Sousa et al. 2008; Ghezzi et al. 2010; Sousa et al. 2011), which seem to be found for a wider metallicity range. However, since RV surveys have only been able to detect very few planets in the terrestrial mass range, there has been no clear understanding of the metallicity relation for the occurrence of small planets.

3.1. Metallicities in the (P, R) Diagram

This problem was recently undertaken by Buchhave et al. (2012) who analyzed metallicity values for a total of 152 KIC stars. Since the metallicities estimated by *Kepler* are photometric and not very precise, Buchhave et al. recalculated some values from very precise spectroscopic measurements. Typical errors for their measurements are of the order of ∼0.08.

Buchhave et al. (2012) find that stellar metallicities are very diverse for small planets ($R < 4\ R_\oplus$), with values between -0.6 and 0.5 with a mean close to $[\mathrm{m/H}] \sim -0.1$. On the other hand, for larger planets, values extend from -0.2 and 0.5 and an average of $[\mathrm{m/H}] \sim 0.15$. These results indicate that while giant planets appear to require high metallicities, smaller planets can form even around very metal-poor stars. These findings are in agreement with similar results by Udry & Santos (2007), Sousa et al. (2011), and Adibekyan et al. (2012).

Buchhave et al. (2012) also found that stellar metallicity is not correlated with the orbital distance of planets. However, they focused on distances of a few tenths of AU, and not on the region closer to the star. In fact, from Figure 2 of their supplementary material, it appears that the region with semimajor axis $a < 0.05$ AU does show a difference with respect to the larger distances.

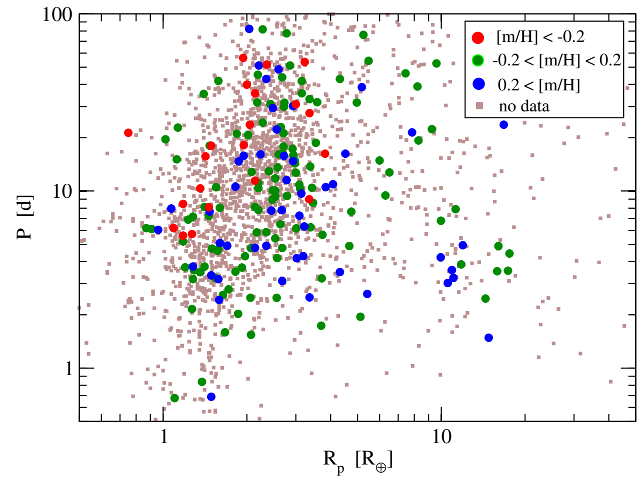

Figure 6. Distribution of *Kepler* candidates in the (P, R) diagram according to their [m/H] metallicity. Data from Buchhave et al. (2012). Color code is defined in the inset.

(A color version of this figure is available in the online journal.)

We used the data kindly provided to us by Lars Buchhave to analyze the metallicity distribution for close-in planets. Results shown in Figure 6 are separated into three intervals: metal-poor, solar metallicity, and metal-rich stars.

The most interesting trend that can be noted in Figure 6 is not in the sub-Jovian mass range, but for small planets ($R < 4\ R_\oplus$). Small planets belonging to metal-poor stars are located beyond $P > 5$ days, while small planets closer to the star tend to have higher metallicities.

Another interesting trend from Figure 6 is the absence of planets with $R > 4\ R_\oplus$ in metal-poor stars. Thus, it appears that in order to form giants or sub-giants, at least a solar metallicity is necessary.

The trends discussed above could be tied to a more pronounced planetary migration (nebular gas disk or planetesimal driven) in systems with a larger solid content, while small planets that formed around metal-poor stars may stay near their formation locations or migrate a lesser amount. Scattering among the small planets could also have played a role. Stars with a higher solid content could tend to form systems of more rocky planets, which would be stable only when their eccentricities are damped by friction (gas or dynamical). Once this stabilization mechanism disappears, close encounters between the planets could lead in some cases to tidal capture and circularization.

A different data set of metallicities has been obtained for RV detections and/or confirmations. Fischer & Valenti (2005) and Sousa et al. (2008, 2011) give [Fe/H] spectroscopic values for almost 600 stars with detected planets. Typical errors are of the order of ∼0.05. The advantage of this source is that it would allow us to incorporate most of the currently known HJs into our study of metallicities and thus have a wider range of planets to analyze. However, we must stress caution, since most of the stars belonging to this data set are located in the solar neighborhood and constitute a different sample from that observed by *Kepler*.

The combined metallicities from both samples are shown, in the (P, R) diagram, in Figure 7. A comparison with Figure 6 shows very similar trends. The paucity of small ($R < 4\ R_\oplus$) planets in metal-poor stars with $P < 5$ days is maintained, even though the number of data points has increased significantly. Actually, the lower limit for metal-poor systems appears to be a diagonal line with orbital periods between 3 and 6 days depending on the planetary radius.

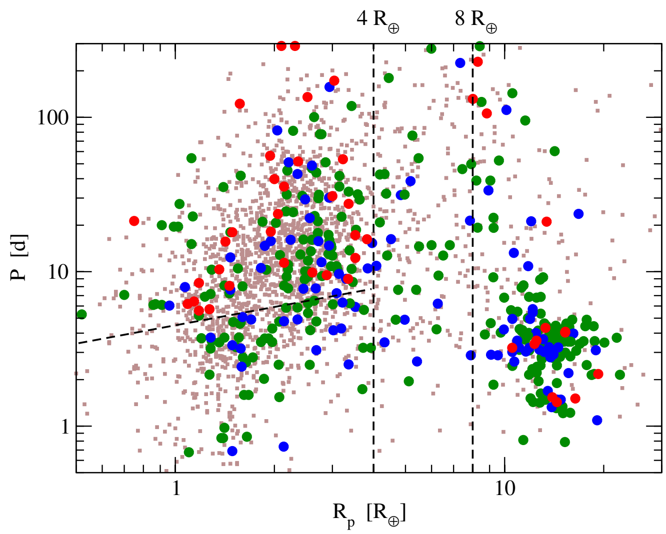

Figure 7. Combined sample of stellar metallicities in the (P, R) diagram, including [m/H] data from Buchhave et al. (2012) and spectroscopic [Fe/H] values from RV surveys (Fischer & Valenti 2005; Sousa et al. 2008, 2011). Color code is same as Figure 6: planets with no available metallicity are shown in small brown squares. Metal-poor stars ($[X/H] < -0.2$) are shown in red, metal-rich stars ($[X/H] > 0.2$) in blue, and stars with solar-type metallicities in green. The diagonal dashed line drawn for small planets is indicative of the lower limit found for metal-poor systems.

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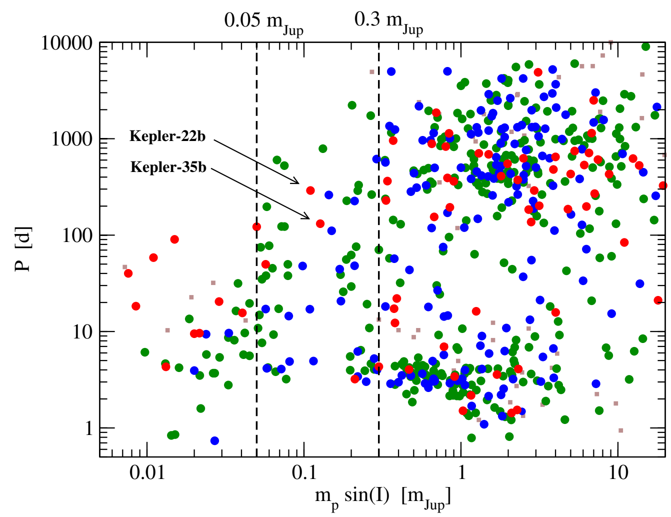

Figure 8. Distribution of stellar metallicities in the $(P, m \sin I)$ plane for confirmed planets with known planetary mass (either true or minimal). Color code is the same as Figures 6 and 7: metal-poor stars in red, solar-type in green, and metal-rich in blue. The vertical dashed lines indicate rough limits for small planets ($m < m_{\rm Nep} \simeq 0.05\, m_{\rm Jup}$) and giant planets ($m > m_{\rm Sat} \simeq 0.8\, m_{\rm Jup}$). See the text for details.

(A color version of this figure is available in the online journal.)

For larger masses, we now observe a number of Jovian planets around metal-poor stars, some of them part of the HJ population in the vicinity of the so-called three day pile-up. However, there seems to be a curious lack of sub-Jovian planets (roughly with $4\ R_\oplus < R < 8\ R_\oplus$) in metal-poor stars for any given orbital period.

To test the statistical significance of these trends, we once again performed a series of Monte Carlo simulations. For the small planets, we identified in Figure 7 the subset of planets with $0.5\ R_\oplus \leqslant R \leqslant 4\ R_\oplus$ and absolute values of metallicities were larger than 0.1. We did not consider planets with $|[X/H]| < 0.1$ so that the resulting data set had a more or less uniform distribution in metallicities. This gave us a set of $N = 99$ planets.

We then ran a series of 10^6 simulations, in which each body was given a new [X/H] value chosen randomly between -0.5 and 0.5 (avoiding absolute values below 0.1) with an uniform distribution function. We counted what number of these synthetic populations had no fictitious planets with $[X/H] < -0.2$ and $P \leqslant 5$ days. The results showed that less than 0.01% of the cases reproduced the observed trend.

For intermediate-size planets, we employed the same process. Although the size of the working population was now smaller ($N = 21$), we placed no limit on the orbital period. Thus, we now counted what percentage of the test runs had no metallicity value $[X/H] < -0.2$. Once again the result was suggestive showing that the observed trend was only reproduced in less than 0.01% of the cases.

3.2. *Metallicities in the (P, m) Diagram*

Since we have so far worked in the period versus planetary radius plane, we have only considered detected exoplanets with transit data. This includes both systems with RV and transit, and systems with only transits (*Kepler*, *CoRoT*, etc.). We therefore did not analyze planets for which only RV data are available and, therefore, have undetermined radius.

One way to include these planets in our study is to plot their distribution in the $(P, m \sin I)$ plane. Not only does this increase the size of our sample, but also allows the use of metallicities determined from RV surveys. The down side is that most of these planets have undetermined orbital inclinations with respect to the line of sight; consequently the masses are minimal values.

Metallicity data were obtained from Fischer & Valenti (2005) and Sousa et al. (2008, 2011), and contain values for almost 600 planet hosting stars. Typical errors are of the order of $\sim$0.05. In particular, Fischer & Valenti (2005) give estimates for five different elements (Fe, Si, Ti, Na, and Ni). The difference between them is of the order of $\sim$0.08. We chose to use [Fe/H] in order to keep the same indicator as presented for HARPS (Sousa et al. 2008, 2011).

The available data have been summarized in Figure 8 and show very similar trends as detected in Figures 6 and 7 for the (P, R) plane. For small planets (i.e., $m \sin I < 0.05\, m_{\rm Jup}$) once again we note that bodies around metal-poor stars are preferably found with larger orbital periods than their metal-rich counterparts.

For intermediate masses ($m_{\rm Nep} < m \sin I < m_{\rm Sat}$), while their distribution in the (P, R) plane showed no planets with $[X/H] < -0.2$, Figure 8 shows 3 cases, two of which are identified in the plot. Kepler-25b is a planet orbiting a stellar binary in a circumbinary orbit (Welsh et al. 2012) and its formation or evolutionary track could be very different from that of planets around single stars. Kepler-22b is the most distant planet *Kepler* has detected so far, with an orbital period of $P = 289$ days. Transit data allow for a fairly precise determination of its radius and correspond to a small planet ($R = 2.3\ R_\oplus$; Borucki et al. 2012). Its mass, however, is not well known. Preliminary values, estimated from 16 RV data points, give $m \sim 0.11\, m_{\rm Jup}$, which would indicate a sub-Jovian planet. Both values are not easy to reconcile. However, given the small number of RV observations, we believe that the location of this planet in the sub-Jovian domain is currently questionable.

The third planet in the sub-Jovian region of the $(P, m \sin I)$ plane is HAT-P-12b (Hartman et al. 2009), a planet with both RV and transit determinations. HAT-P-12b has a mass of

$m = 0.21\, m_{\rm Jup}$ and $P \sim 3$ days, placing it barely within the sub-Jovian range (arbitrarily defined), and a radius $R = 11\ R_\oplus$, implying the smallest planetary density ($\rho \sim 0.3$ g cm^{-3}) known to date.

Summarizing, it appears that there are practically no detected sub-Jovian planets with metallicities below -0.2. This could imply that these bodies are uncommon, or that they are located beyond $P \sim 100$ days, just as in our own solar system.

4. DISCUSSION

We have shown new evidence for a significant paucity of planetary bodies with radii roughly between 3 and 10 $R_\oplus$ and orbital periods below ~3 days. This region is completely void of confirmed planets and *Kepler* multiplanet candidates, and was christened by Szabo & Kiss (2011) as a sub-Jovian desert. However, approximately 16 single-planet *Kepler* candidates are located within this region of the (P, R) plane. We find that at least seven of them are probably FPs. Since we cannot rule out the rest, we prefer to refer to this region as a sub-Jovian Pampas.

The origin of this Pampas is not obvious. It could be related to the effect of atmospheric evaporation (Youdin 2011) which is expected to be especially effective in planets with large gas envelopes and low surface gravity. Very close to the star, atmospheric evaporation would not be effective in planets with high surface gravity (such as Jovian bodies) but could readily strip the volatiles from smaller planets leaving behind the solid cores. In consequence, while most of the HJs would not be significantly affected, the observed radius of smaller planets would decrease over time leading to a depletion of this region.

Although Youdin (2011) only proposes such a mechanism for relatively small planets ($R \sim 3$–$5\ R_\oplus$), it may be applicable to a larger interval. Extrapolating from his idea, the depletion of hot Neptunes would not be complete if sub-Jovian planets originally have very diverse core sizes (relative to their gas envelopes). The change in the planet radius due to atmospheric evaporation would then not be equally effective for all of them. The result would then be a *partial* depletion of the region, causing the appearance of the observed sub-Jovian Pampas. However, it is difficult to estimate whether this effect would be effective even up to planetary radii close to Jovian values.

Another possibility is dynamical in nature. In Beaugé & Nesvorný (2012) we showed that a dynamical tide model (e.g., Ivanov & Papaloizou 2011) for quasi-parabolic orbits is necessary in order to allow tidal trapping sufficiently far from the central star to avoid stellar engulfment. Dynamical tides, however, are expected to be inefficient for planets with most of its mass in solids (as opposed to gas-rich planets such as Jupiter). Consequently, if the sub-Jovian planets have large cores and light atmospheres, then dynamical tides would not have being able to tidally trap the planets sufficiently far from the star to avoid tidal engulfment, leading to a sparsity of such planets close to the star.

With respect to the distribution as a function of stellar metallicity, the lack of super-Earths with small orbital period around metal-poor stars may point to a delayed formation of these planets, implying a smaller radial range of planetary migration. The paucity of planets with $R \simeq 4$–$8\ R_\oplus$ around metal-poor stars with orbital periods up to 100 days is also interesting, and could indicate that Neptunes around metal-poor stars did not migrate far and are all located beyond 100 days.

A word of caution at this point. We have assumed that the metallicity index [Fe/H] is a proxy for planetary formation. Gonzalez (2009) points out that abundance of other heavy elements (Mg, Si), which together with Fe define the so-called refractory index "Ref," could also be important. In their recent survey of chemical abundances for 1111 FGK stars from the HARPS GTO planet search program, Adibekyan et al. (2012) indicate higher [Ref/H] values for Neptune-size planets than [Fe/H] alone. However, the role and relative importance of different refractory materials is not yet firmly established, so it is unclear how using [Ref/H] instead of [Fe/H] could affect our results.

The trends pointed out in this paper are preliminary and we believe they deserve future scrutiny. Future planetary detections and confirmations should be able to validate (or rule out) these trends and allow for a better interpretation of their origin.

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REFERENCES

Adibekyan, V. Zh., Sousa, S. G., Santos, N. C., et al. 2012, A&A, 545, A32
Beaugé, C., & Nesvorný, D. 2012, ApJ, 751, 119
Benítez-Llambay, P., Masset, F., & Beaugé, C. 2011, A&A, 528, A2
Bonomo, A. S., Chabaud, P. Y., Deleuil, M., et al. 2012, A&A, 547, A110
Borucki, W. J., Koch, D. G., Basri, G., et al. 2011, ApJ, 736, 19
Borucki, W. J., Koch, D. G., Batalha, N., et al. 2012, ApJ, 745, 120
Buchhave, L. A., Latham, D. W., Johansen, A., et al. 2012, Natur, 486, 375
Colón, K. D., Ford, E. B., & Morehead, R. C. 2012, MNRAS, 426, 342
Fischer, D. A., & Valenti, J. 2005, ApJ, 622, 1102
Ghezzi, L., Cunha, K., Smith, V. V., et al. 2010, ApJ, 720, 1290
Gonzalez, G. 2009, MNRAS, 399, L103
Hasegawa, Y., & Pudritz, R. E. 2012, ApJ, 760, 117
Hartman, J. D., Bakos, G. Á., Torres, G., et al. 2009, ApJ, 706, 785
Howard, A. W., Marcy, G. W., Johnson, J. A., et al. 2010, Sci, 330, 653
Howard, A. W., Marcy, G. W., Bryson, S. T., et al. 2012, ApJS, 201, 15
Ida, S., & Lin, D. N. C. 2004, ApJ, 604, 388
Ivanov, P. B., & Papaloizou, J. C. B. 2011, CeMDA, 111, 51
Johnson, J. A., Aller, K. M., Howard, A. W., & Crepp, J. R. 2010, PASP, 122, 905
Koch, D., Borucki, W. D., Edward, G. J., et al. 2004, Proc. SPIE, 5487, 1491
Latham, D. W., Rowe, J. F., Quinn, S. N., et al. 2011, ApJL, 732, 24
Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, Natur, 380, 606
Lissauer, J. J., Marcy, G. W., Rowe, J. F., et al. 2012, ApJ, 750, 112
Mayor, M., Marmier, M., Lovis, C., et al. 2011, A&A, submitted (arXiv:1109.2497).
Mordasini, C., Alibert, Y., & Benz, W. 2009, A&A, 501, 1139
Mordasini, C., Alibert, Y., Georgy, C., et al. 2012, A&A, 547, A112
Morton, T. D., & Johnson, J. A. 2011, ApJ, 738, 170
Nagasawa, M., Ida, S., & Bessho, T. 2008, ApJ, 678, 498
Naoz, S., Farr, W. M., & Rasio, F. A. 2012, ApJL, 754, 36
Ofir, A., Alonso, R., Bonomo, A. S., et al. 2010, MNRAS, 404, L99
Ofir, A., & Dreizler, S. 2012, A&A, submitted (arXiv:1206.5347v1)
Santerne, A., Díaz, R. F., Moutou, C., et al. 2012, A&A, 545, A76
Santos, N. C., Israelian, G., & Mayor, M. 2004, A&A, 415, 1153
Santos, N. C., Mayor, M., Binfils, X., et al. 2011, A&A, 526, A112
Sousa, S. G., Santos, N. C., Israelian, G., Mayor, M., & Urdy, S. 2011, A&A, 533, A141
Sousa, S. G., Santos, N. C., Mayor, M., et al. 2008, A&A, 487, 373
Szabo, Gy. M., & Kiss, L. L. 2011, ApJL, 727, 44
Udry, S., & Santos, N. C. 2007, ARA&A, 45, 397
Welsh, W. F., Orosz, J. A., Carter, J. A., et al. 2012, Natur, 481, 475
Youdin, A. N. 2011, ApJ, 742, 38