Hot Big Planets Survey: Measuring the Repopulation Rate of the Shortest-Period Planets

Stuart F. Taylor

Participation Worldscope
Sedona, Arizona, USA
astrostuart@gmail.com

Abstract

By surveying new fields for the shortest-period "big" planets, the Kepler spacecraft could provide the statistics to more clearly measure the occurrence distributions of giant and medium planets. This would allow separate determinations for giant and medium planets of the relationship between the inward rate of tidal migration of planets and the strength of the stellar tidal dissipation (as expressed by the tidal quality factor Q'_*). We propose a "Hot Big Planets Survey" to find new big planets to better determine the planet occurrence distribution at the shortest period. We refer to the planets that Kepler will be able to find as "big", for the purpose of comparing the distribution of giant and medium planets above and below 8 earth radii ($R_\oplus$).

The distribution of planets from one field has been interpreted to show that the shortest period giant planets are at the end of an ongoing flow of high eccentricity migration, likely from scattering from further out. The numbers of planets at these short periods is still small, leaving uncertainty over the result that the distribution shows the expected power index for inward tidal migration. The current statistics make it hard to say whether the switch between more medium planets at most periods but more giant planets at the shortest periods indicates a greater migration of giant than medium planets.

We propose a repurposed Kepler mission to make enough 45-day observations to survey 10 times as many stars as in Kepler's survey of the original field, to survey for planets with periods of up to fifteen days with at least three transits. This would better measure the occurrence distribution in the period range that will include planets migrating into the star. We seek to measure the relative rate of migration of giant and medium planets at the shortest periods. Results from ground surveys and from surveying the first Kepler field show a dropoff in the distribution that can be attributed to stellar tides causing planets to undergo inward migration into the star, but currently available statistics are still low, producing only very uncertain measurements of the parameters of the innermost distribution.

Studying the innermost occurrence distribution will not only allow studying tidal migration, it will allow study of why are many of the short period giants planets inflated. It would find out if planets sometimes become smaller due to atmospheric blowoff. Separating out these three effects requires better statistics than those from one Kepler field. More planets can be found by moving to new fields. Short period planets are found much more rapidly than longer period planets. Only a dedicated space-based survey can provide planet occurrence statistics that do not have the hard-to-quantify biases of ground-based surveys. Surveying many fields for as many planets as possible will provide an important baseline for TESS and other studies.

1 Introduction

The Kepler mission has provided a wealth of statistics on the occurrence distribution of planets. Statistics from the Kepler mission are much more reliable than statistics from ground based surveys due to difficulty in understanding the day/night window function of transit surveys and the varying systematics of all ground surveys. Now that the Kepler spacecraft will have less photometric precision due to operating with only two reaction wheels, NASA has called for submissions of alternative mission concepts. The spacecraft will be unable to continue pursuing its original goal of observing transits of planets of radii the order of the earth in year-long orbits. We propose that Kepler do what transit surveys do best: Find the highest number of "big" radii planets as possible by observing many fields. We call this the "Hot Big Planets Mission", where we define "big" to include from the largest planets down to whatever radii Kepler is still able to detect. We refer to planet candidates as "planets", even for objects possibly too large to be planets. Though we hope Kepler will still be able to detect smaller planets, our purpose here is to show the value of comparing the occurrence distribution of planets above and below 8 earth radii ($R_{\oplus}$).

The measurement of the shortest period occurrence distribution obtained using data from one Kepler field has shown tantalizing patterns that are still unresolved by the available statistics. We are left with the mystery of how there are some planets so close to the star that it is improbable to have found them in the last short time period before their merger with the star, as would be expected if the tidal migration is similar to that measured for binary stars (Hamilton, 2009; Hebb et al., 2010; Birkby et al., 2013; Meibom & Mathieu, 2005). The shortest period occurrence distribution of giant planets has lead to work concluding that tidal dissipation on stars caused by tides raised by planet-mass companions is unexpectedly weak (Penev et al., 2012). The number of giant planets at the shortest periods is in relative excess to the number of medium planets, and the distribution of planets from 4 to 8 $R_{\oplus}$ can be explained with a stellar tidal migration strength not excessively weaker than that measured for binary stars. This has been used by Taylor (2012b, 2013b, hereafter T12b,T13b) to show that the occurrence distribution of could be explained by the migration of giant planets ("flow") proposed by Socrates et al. (2012) which could repopulate the shortest period occurrence distribution as planets are lost to inward migration due to tides on the star. With such a flow, the tides on stars need not be weaker for planetary mass companions than they are for stellar mass companions. Though Kepler has found many planet candidates, the observation of one field has not provided enough of the closest planets to show the planet occurrence distribution as a function of radii clearly enough to separate out the effects of tidal migration from changes (up or down) in planet radii. It is easy to forget that the shortest period planets are actually quite rare – a fact obscured by how transit surveys find the closest planets much more easily. Kepler will find more planets faster if it observes for 45 days and then moves to a new field. By observing many fields, it will provide important statistics that will show what happens as planets tidally migrate into their stars.

The one-field Kepler data has been interpreted to show that giant and medium planets undergo tidal migration when they get too close to the star (T12b,T13b, Taylor (2012a, 2013a, Taylor 2012a, Taylor 2013a; hereafter T12a,T13a)), but the uncertainty in the fits (Howard et al., 2012, hereafter H12) are too high to be certain we see current inward migration rather than the distribution left over when the protoplanetary disk dissipated. However, the small numbers of planets leaves noise that obscures whether the patterns have more detail that could help show whether other factors could affect the distribution. The small numbers of planets from one Kepler field give the distribution insufficient clarity to consider how changes in radii could affect the distribution. There is reason to believe that planets can inflate or can suffer atmospheric loss. True, mass measurements will also be important to study these problems, but there will still be too few planets at short periods to separate out the effects of tidal migration and the changes in radii, either up or down, that planets can experience as they migrate to merger with the star.

We propose a repurposed Kepler mission to conduct observations of several new fields for periods of 45 days with the objective of better measuring the occurrence distribution of "Hot Big Planets" (HBP), that is, short-period planets of giant and intermediate radii. Even if Kepler is only able to monitor half as many stars in each new field as in the orginal field, the number of stars surveyed for planets of periods of fifteen days or less would be increased by a factor of four each year. We hope that five to ten fields could be observed. It would likely be possible to still find planets in 15 day periods with three 15 day observations spaced to find longer period planets.

We show that there are important questions of the nature of planets, stars, and their interactions that are best measured by improving the statistics of big planets. We highlight the differences in the distribution of "giant" (>8 earth radii, $R_{\oplus}$) and "medium" (4 to 8 $R_{\oplus}$) radii planets in current Kepler data, but point out that because these shortest period planets are in fact relatively rare (despite their over-representation in early discoveries) that there remains large uncertainties in the occurrence distribution of planets at periods of a few days. There appears to be an excess of giant relative to intermediate planets at the shortest periods, given that at slightly longer periods, there are more intermediate planets.

It appears hopeful that the two-wheeled mission may still find planets sufficiently below 8 $R_{\oplus}$) to characterize the distribution of medium radii planets. There appears to be a difference in the occurrence rates of planets from 6 to 8 $R_{\oplus}$ compared to planets larger than 8 $R_{\oplus}$, so we hope that new observations will be able to reach a precision of 0.36% (and being able to count planets of radii of 5 or 4 $R_{\oplus}$ would be even better). However, we see in Figure 4 that there are interesting differences even in planets with radii from 8 to 11.3 $R_{\oplus}$, 11.3 to 16 $R_{\oplus}$, and above 16 $R_{\oplus}$.

Improved knowledge of the occurrence distribution of "big planets" at the shortest period would improve understanding of the evolution and properties of interacting planets and stars. Kepler will still be able to search for "big" planets, which we define to be of Jupiter and Neptune size, which we call "giant" and "medium" sized planets. The Kepler mission has already greatly improved measurements of this closest region with its continuous and unbiased coverage of one field of stars, but the quality of statistics currently available from Kepler observations are still limited by low number statistics, because planets at the shortest periods are actually rare. Though in early discoveries of planets, planets with the shortest periods were overrepresentated due to their relative ease of discovery. However, ground based surveys have poorly studied systematics and window functions which makes it difficult to reliably assess their rate of discovery, leading to uncertainty in how good the occurrence functions derived from ground surveys really are.

We propose a goal of observing ten times as many stars as observed in the Kepler field for a period of 45 days. Even if current limitations and new fields only allow monitoring 75,000 stars at a time, half as many stars as the original 150,000, then observing each year of observing new fields could still achieve four times the statistics of the original Kepler mission. Even 30 day observations would improve statistics of 10 day and below planets, and depending on the reliability of only having two transits, may still be useful for statistics of planets with up to 15 day periods. Other than observing new fields for 45 days, the details of this survey will be similar to the nominal mission. Selection of the fields is beyond one paper, but the first field could be from the alternate fields considered for the nominal mission. Finally, it may be possible to break up the observations in 15 day pieces to allow surveying of longer period planets as well. This project is highly flexible in choice of fields to allow for other types of observations.

The new fields could be selected to include a wider range of star ages, with an effort being made to include younger stars and more stars in clusters, in order to look for changes of the planet occurrence function with age. This would allow determining whether the difference in the three-day pileup of giant plants between the Kepler field and the solar neighborhood is due to a different distribution of stellar ages.

We discuss the difference in giant versus medium planet distributions in Section ??. We show how obtaining a clear measurement of the distribution of such "big" planets will allow for determination of the relationship between the rate of migration of planets and the strength of the tidal dissipation in stars, $1/Q'_*$, in Section 2. We review the evidence for ongoing migration of planets in Section 3.

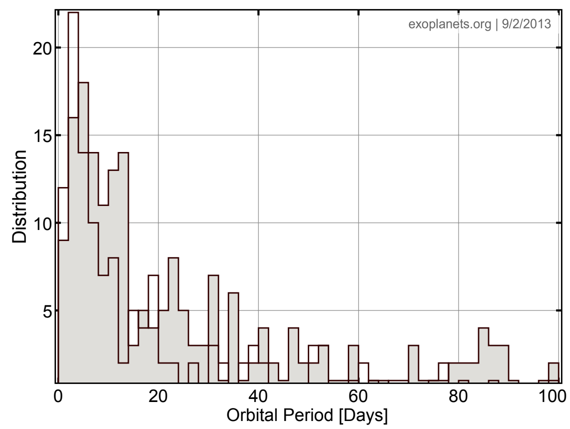


Figure 1 Raw counts of linear bins of Kepler planet (candidates) with radii greater than 4 $R_\oplus$, divided into two ranges: The count of "giant" (8 to 16 earth radii, $R_\oplus$) are shown by unfilled bins, that of "medium" (4 to 8 $R_\oplus$) planets are shown by filled bins.

2 Objective: Improve Statistics of Big Planets to Study Tidal Migration, Tidal Dissipation, and More

Studying planet migration is an important rationale for observing new fields to find new big planets. The occurrence distribution for Kepler planet candidates with periods up to 100 days is shown in Figure 2, where the counts of planets has been normalized by the transit probability and divided by the number of stars observed. We also show the raw counts in Figure 3 in order to display how many counts the results in Figure 2 rely on. We see important features in Figure 3, but comparison with Figure 2 shows interesting features that rely on only a few points.

We highlight three features of the shortest period planet distribution:

- The falloff of the giant and medium planets has a power index close to that predicted for tidal migration into the star.
- Though the number of giant planets is generally less than the number of medium planets

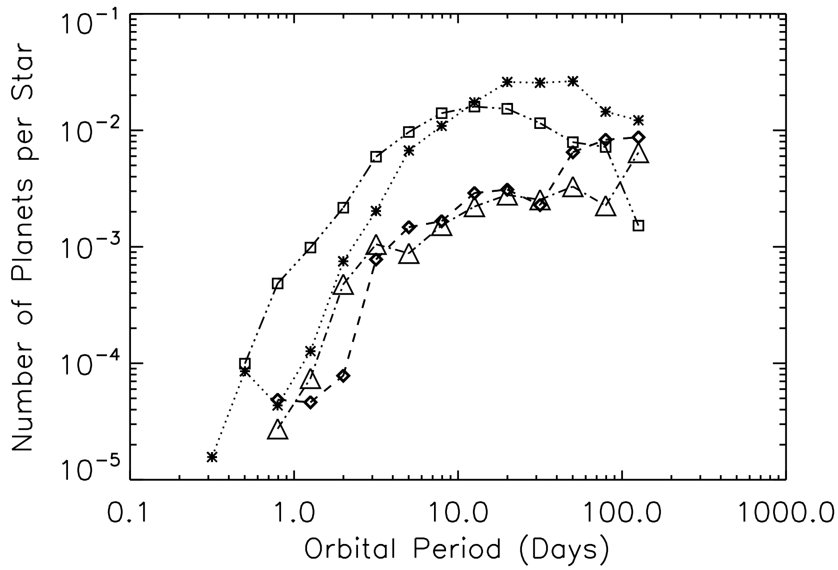


Figure 2 Counts of Kepler "planet candidates" normalized by transit probability divided by the number of stars, and counted in logarithmic bins to give the "occurrence distribution" of planets. These normalized counts have been divided into four ranges in radii. The normalized count of "giant" (8 to 16 earth radii, $R_\oplus$) are shown by triangles, that of "medium" (4 to 8 $R_\oplus$) planets are shown by diamonds, that of "medium-small" (2 to 4 $R_\oplus$) planets are shown by asterisks, and that of "small" (2 to 4 $R_\oplus$) planets are shown by squares.

for periods greater than a few days, there is a relative excess of giant planets going from the pileup at three day periods down to periods on the order of a day.

- The falloff of medium and medium small planets appears to flatten out at periods less than two days for medium planets and less than one day for medium small planets.

Each of these features, when compared to Figure 2, depends on a number of planets too small to definitively make these conclusions. It is in these few day range that details of tidal migration as well as details of the inflation of planets or the blowoff of planet atmospheres can be expected to become visible.

The shortest period distribution has three key parameters: the power index of the fall off, the location of the fall off, and the power index of the distribution beyond the fall off (H12).

An HBP survey would provide enough statistics to know the power index and position of the falloff well enough to determine whether the falloff of giant planets being at a shorter period than for medium planets is due to giant planet migration, or due to the nature of tidal dissipation in the star.

It is also desirable to look for whether the distribution changes with the age of the system, or with changes in other parameters such as stellar mass, but there needs to be more planets to be able to subdivide these statistics by age.

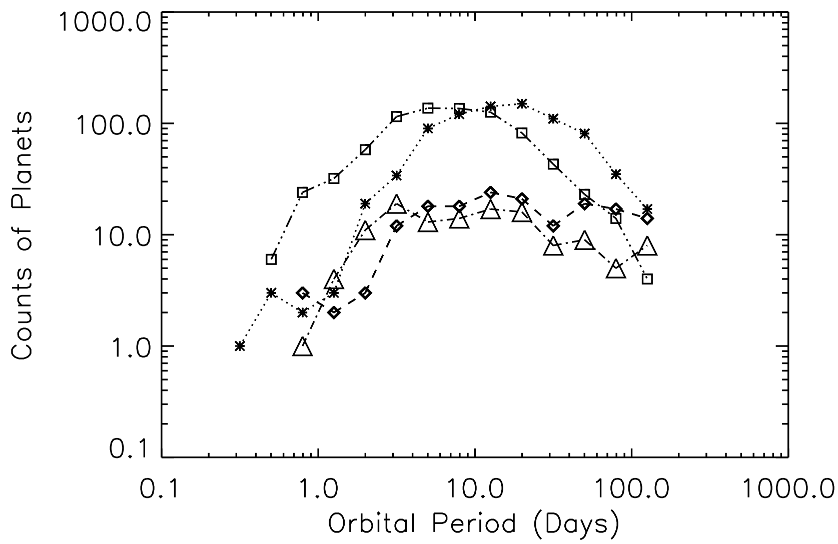


Figure 3 Raw Counts (not normalized) in logarithmic bins of the observed transiting Kepler planets divided into four ranges in radii. The normalized count "giant" (8 to 16 earth radii, $R_{\oplus}$) are shown by triangles, that of "medium" (4 to 8 $R_{\oplus}$) planets are shown by diamonds, that of "medium-small" (2 to 4 $R_{\oplus}$) planets are shown by asterisks, and that of "small" (2 to 4 $R_{\oplus}$) planets are shown by squares.

3 More giant than medium planets at shortest periods: Weak tides or migration?

Kepler results as presented in Figure 2 show more giant planets than medium planets at the shortest periods, even though there are more medium planets further out. Tidal migration is faster for more massive planets, so T12b and T13b present this as evidence that giant planets regularly migrate into the star. finds that for a tidal dissipation constant of $Q'_* \sim 10^6$ that roughly than 10^{-12} planets per star per year would be needed to maintain the observed distribution of planets migrating into the star; if $Q'_* \sim 10^7$, only a few times 10^{-13} planets would be required.

Hamilton (2009); Hellier et al. (2009) present how finding a planet of as short a period as that of WASP-18 is unlikely given how soon it will merge with the star, unless it will not tidally migrate into the star as fast as currently thought. Penev et al. (2012) interpret the occurrence distribution to give a value of Q'_* much higher than 10^7, but this distribution could also be interpreted as an excess due to lower Q'_* with the short period planets continually repopulated by a flow.

Inward tidal migration operating on a planet occurrence distribution that is initially as a power law will produce a fall off with a power index of 13/3 (T12a,T12b). This is close to the power index of the fall off found by H12. However, the limited number of planets causes large uncertainties in the H12 fits, leaving it uncertain whether the power index is close to 13/3 by chance.

An inward flow of highly eccentric planets was postulated by Socrates et al. (2012), but paucity of high eccentricity planets was seen by Dawson et al. (2012). However, the expected numbers of planets expected by Socrates et al. (2012) is only a few in the single Kepler field. Statistics from many fields could resolve this discrepancy.

Several reports demonstrate that planets of iron-rich and iron-poor stars form two populations,

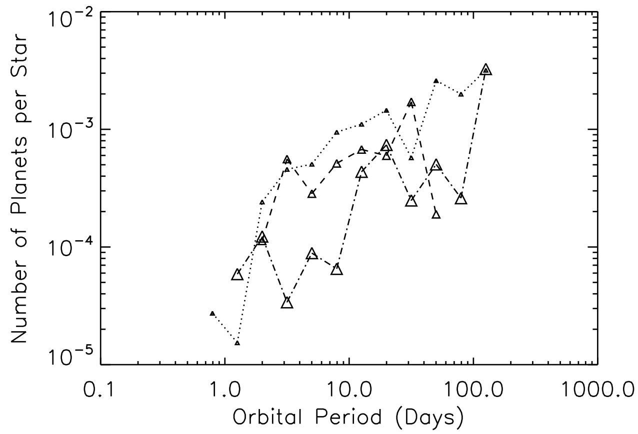


Figure 4 Normalized counts of Kepler "planet candidates" above 8 $R_\oplus$, divided into three radii ranges, where the smallest triangles indicate the smallest radii planets, 8 to 11.3 $R_\oplus$, the medium range is 11.3 to 16 $R_\oplus$, and the largest is above 16 $R_\oplus$.

with evidence of more crowded formation and more scattering in the iron-rich systems.

Dawson & Murray-Clay (2013, hereafter DM13) show correlation and that the three-day pileup is a feature of the metal rich population, but is still low in the Kepler field. Having fields with different populations by observing stars in different parts of the galaxy would allow checking whether the pileup is dependent on location in the galaxy. This could also allow checking on whether the pileup is affected not only by metallicity but whether as H12 suggested it could be dependent on the age profile which changes as a function of distance from the galactic plane.

Several authors find evidence of two populations of planets, with a more crowded population likely characterized by more giant planet migration. DM13 and T13b find that the distribution of iron-rich and iron-poor systems have dramatically different patterns that are likely associated with different amounts of scattering in the two populations. These observations were prompted by the discovery that planet orbit eccentricity is correlated with stellar [Fe/H] (T12b and DM13). Xie et al. (2013) find two populations of planet systems: closely versus sparsely packed, with the closely packed systems characterized by more transit timing variations than sparsely packed systems.

Finding more planets is the best way to explore these abundance-dependent patterns. With all the patterns that have been found at longer periods providing evidence for inward migration playing a major role in planetary systems evolution, it is important to obtain better detail in the shortest period regions.

This sets up a debate with the previously preferred explanation for the discovery by ground surveys of planets at periods so short that finding them this close to the star should be very unlikely if the expected strength of tidal dissipation in stars is to be believed. Hamilton (2009) and others explain that it should be unlikely to have found number planets that appear to be in the last small fraction of their existence before being made to tidally migrate into the star.

However, the fit by H12 to the distribution of medium planets found by Kepler when compared to the distribution due to tidal dissipation as shown by Figure 5 from T12b and T13b shows that Q'_* need not be any weaker than 10^7. We see in Figure 5 that the power index found by H12 corresponds well to the power index produced by tidal infall of the planet. The tidal migration into the star is fast enough in the falloff region even under weak tidal dissipation that the position

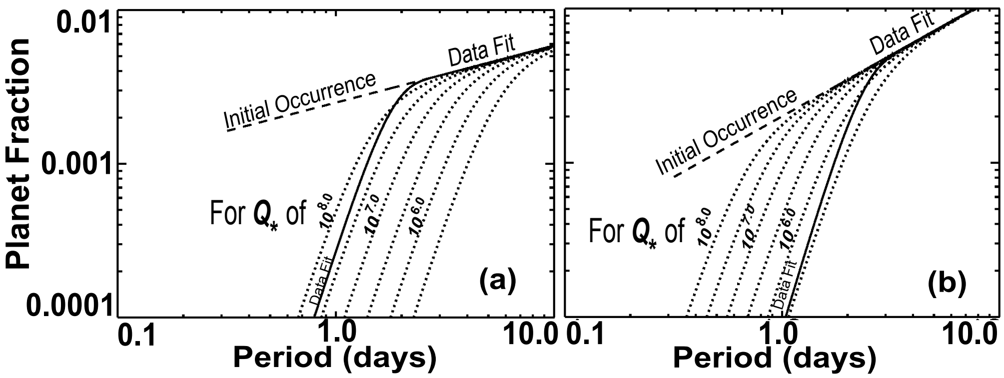
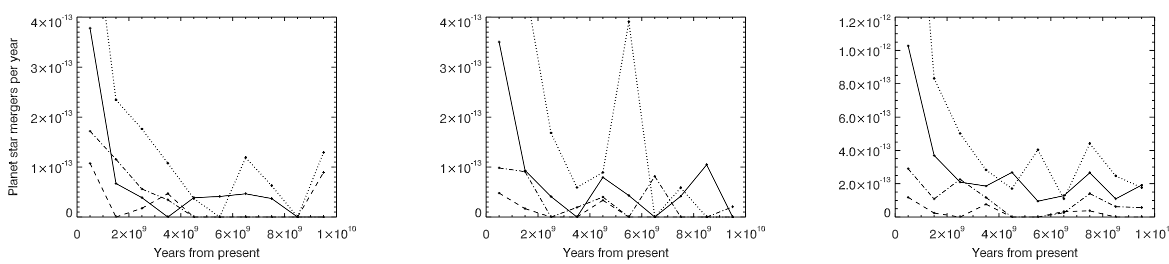


Figure 5 Measured versus simulated occurrence distributions for short periods for (a) giant planets (summed for masses from 100 to 2000 $M_{\oplus}$ and radii from 8 to 32 $R_{\oplus}$) and (b) medium planets (summed for masses from 10 to 100 $M_{\oplus}$ and and radii from 4 to 8 $R_{\oplus}$). Fits to Kepler occurrence data from H12 are compared to calculated distributions for a range of tidal dissipation strengths from weak to strong. The left dotted-line curve is for a weak dissipation of Q'_* of $10^{8.5}$ with each next line representing a factor of $10^{0.5}$ stronger dissipation, up to a dissipation strength of Q'_* of $10^{6.5}$. The simulated distributions were calculated starting from an initial occurrence distribution with no inner drop off, shown as a dashed line, and were summed for a representative range of system ages.



(a) Infall rate of 8-16 $R_{\oplus}$ planets. (b) Infall rate of 4-8 $R_{\oplus}$ planets. (c) Infall rate of 2-4 $R_{\oplus}$ planets.

Figure 6 Future planet/star mergers calculated for actual Kepler candidates which are weighted to give a rate that can be compared to the future merger rate presented in T13b. We show connected points for dissipation values of Q'_* values of $10^{6.5}$ (dotted, top), with each lower line representing a tidal dissipation weaker by a factor of $10^{0.5}$, down to a strength of Q'_* of $10^{8.5}$. Though the use of individual data points makes these results more noisy, the results are consistent with those from using the fit. that the tidal dissipation is unlikely to be as strong as Q'_* of $10^{6.5}$ as this would result in an unphysical increase in merger rate when planets beyond the fall-off migrate into the star.

of the falloff is not much dependent on the initial distribution (T12b,T13b). The biggest problem with interpreting the location of the falloff and the power index is the uncertainty of the values from the fit of H12 due to the low numbers of planets available.

We show the occurrence distributions of giant, medium, super-earth radii range planets in Figures 2, which is normalized for transit probability and the number of stars surveyed. To show that many of the important features in these distributions rely on counts of small numbers, we show in Figure 3 what the actual unnormalized counts for Figures 2 are. The falloff due to tidal dissipation is still poorly defined – the fit of has a fall-off power index close to the value expected from tidal migration of 13/3 (T12b,T13b) but has high uncertainty. The differences between the medium and giant planets, and the location of the giant planet fall-off at shorter periods than the fall-off of medium planets, rely on only a few counts.

When using Kepler planet data to compare what the future infall rate of giant versus medium planets would be, we again run into trouble with low statistics. Though when using a fit, as in shown in T13b, we can make a case that the current occurrence distribution cannot maintain a continuous infall of giant planets into the star without being supplemented by a flow of tidally migrating giant planets, this result is uncertain due to the large uncertainty in the values of the fit. This can also be seen by the noisy result of using the actual Kepler planets to calculate when planets will infall, as shown in Figure 6.

The rate of planets required to maintain an infalling population of shortest-period planets is still less than 10^{-12} planets per star per year (T13a,T13b) a rate that would not unreasonably depopulate the reservoir of more distant planets.

4 Conclusions

More clearly measuring the shortest period distribution of giant and medium planets will show if there is significant migration of giant planets into the star, or if the stellar tidal dissipation is weaker for planet mass than for stellar mass companions. Such a measurement will also allow establishing the relationship between the stellar tidal dissipation constant Q'_* and the rate of planet migration into the star. Finding more of the shortest period planets will prepare baseline measurements of transit times that will in not too many years enable either measuring or placing a strict upper limit on the change of transit times, which will allow either determination of Q'_* or a strict upper limit on its maximum strength.

The HBP survey makes the best use of what Kepler is optimized for: finding planets in short periods. The transit method is best suited to finding the shortest period planets. Planets found by Kepler do not suffer the effects of observing only at night, so the resulting counts are more robuts than counts of planets found by ground-based surveys. Kepler was designed to find planets, and it still will do well finding planets, even if it does not find not as small of planets as it could before.

Many other proposed uses of Kepler will also propose surveying multiple fields, so the HBP mission is compatible with other projects that require periods on the order of one month.

This white paper gives reasons why statistics of planets in the range of one to several days has special value. These statistics will enable further understanding the end result of tidal migration of planets. Learning the rate at which planets migrate into the star is an important parameter for determining the rate of planet scattering.

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A APPENDIX A: Tidal migration equations

Tidal migration due to tides on the star is proportional to the planets mass. Once planet orbits are circularized, tidal migration faster for more massive planets.

Tidal migration equations of Jackson:

$$\frac{1}{a}\frac{da}{dt} = -\left[\frac{63}{2}(GM_*^3)^{1/2}\frac{R_p^5}{Q_p' M_p}e^2 + \frac{9}{2}(G/M_*)^{1/2}\frac{R_*^5 M_p}{Q_*'}\left(1+\frac{57}{4}e^2\right)\right]a^{-13/2} \tag{1}$$

For the eccentricity evolution, we use the equation of Jackson et al. (2009),

$$\frac{1}{e}\frac{de}{dt} = -\left[\frac{63}{4}(GM_*^3)^{1/2}\frac{R_p^5}{Q_p' M_p} + \frac{225}{16}(G/M_*)^{1/2}\frac{R_*^5 M_p}{Q_*'}\right]a^{-13/2} \tag{2}$$