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Letter to the Editor

Tidal dissipation and the formation of *Kepler* near-resonant planets

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ABSTRACT

Multiplanetary systems detected by the *Kepler* mission present an excess of planets close to first-order mean-motion resonances (2:1 and 3:2), but with a period ratio slightly higher than the resonant value. Several mechanisms have been proposed to explain this observation. Here we provide some clues that indicate that these near-resonant systems were initially in resonance and reached their current configuration through tidal dissipation. It has been argued that this only applies to the close-in systems and not to the farthest ones, for which the tidal effect is too weak. Using the KOI catalog of the *Kepler* mission, we show that the distributions of the period ratio among the most close-in and the farthest planetary systems differ significantly. This distance-dependent repartition is a strong argument in favor of the tidal dissipation scenario.

Key words. celestial mechanics – planets and satellites: general

1. Introduction

The *Kepler* mission has opened the opportunity to perform statistical studies on a considerable number of planets. More specifically, the large number of planets detected in multiplanetary systems allows testing the formation and evolution scenarios of planetary systems. One of the most surprising results obtained by the *Kepler* mission was the fact that only a small fraction of planet pairs are locked in first-order mean-motion resonances (2:1, 3:2), while a significant excess of pairs is found with a period ratio close to but higher than the resonant value (Lissauer et al. 2011; Fabrycky et al. 2012). We reproduce in Fig. 1 the distribution of the period ratio of planet pairs close to these first-order resonances using the Q1-Q16 *Kepler* object of interest (KOI) catalog (Batalha et al. 2013). This data set contains both confirmed planets and unconfirmed planet candidates. Candidates that are known to be false positives are removed from the sample. We observe, as described in the literature, an excess of planet pairs with a period ratio higher than the resonant value (see Fig. 1).

Different explanations for this observation have been proposed, which involve tidal dissipation raised by the star on the planets (Lithwick & Wu 2012; Delisle et al. 2012, 2014; Batygin & Morbidelli 2013), dissipative effects between the planets and the proto-planetary disk (Rein 2012; Baruteau & Papaloizou 2013; Goldreich & Schlichting 2014), between planets and planetesimals (Chatterjee & Ford 2014), or in-situ formation (Petrovich et al. 2013; Xie 2014). In this article we provide some statistical clues in favor of the scenario involving tidal dissipation in planets that are initially locked in resonance.

The phenomenon of resonant departure induced by tidal dissipation was described by Papaloizou & Terquem (2010) and Papaloizou (2011) and has been analyzed with a particular focus on *Kepler* statistics by different authors (Lithwick & Wu 2012; Delisle et al. 2012; Batygin & Morbidelli 2013). These studies showed that for close-in planetary systems an excess of planets

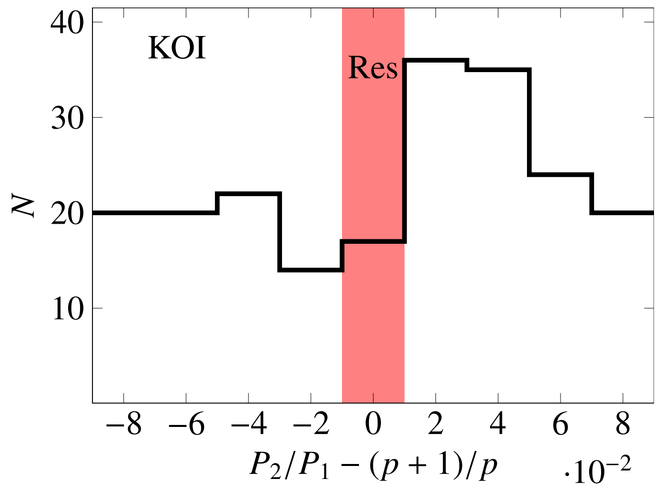

Fig. 1. Distribution of the period ratio between pairs of planets close to the 2:1 and 3:2 mean-motion resonances. The distributions around both resonances are accumulated to obtain a more meaningful set of systems. These statistics are obtained from the Q1-Q16 KOI catalog (Batalha et al. 2013). The origin of the x-axis is the exact commensurability of the periods (resonant systems) and is highlighted with a red strip. Negative values correspond to internal circulation ($P_2/P_1 < (p+1)/p$), positive values to external circulation ($P_2/P_1 > (p+1)/p$). We observe a strong excess of systems in external circulation, with $P_2/P_1 - (p+1)/p \approx 2 \times 10^{-2}$.

similar to the observed excess is naturally produced by tidal dissipation raised on the planets by the stars.

Recently, Lee et al. (2013) showed that this scenario is too slow to explain the typical distance of planet pairs to the nominal resonance ($P_2/P_1 - (p+1)/p \approx 2 \times 10^{-2}$) on a reasonable timescale. In Delisle et al. (2014), we showed that tidal dissipation raised by the star in the innermost planet induces an increase of the amplitude of libration in the resonance. If the initial amplitude of libration (at the time when the protoplanetary disk disappears) is significant, the system is able to cross the separatrix and leave the resonance while the eccentricities of the planets are still high ($e_1 \gtrsim 0.15$). The subsequent evolution of the period ratio of the planets is in this case 3−5 orders of magnitude higher than in the scenario of departure at low eccentricities considered by Lee et al. (2013)[1] because the tidal effect becomes more efficient with increasing eccentricities (see Delisle et al. 2014, Sect. 5). Therefore, many systems that were discarded by Lee et al. (2013) might have evolved from the resonance to their current configuration by tidal dissipation, following this new scenario. Assuming a large initial amplitude of libration in the resonance is not absurd. Goldreich & Schlichting (2014) showed that during the phase of migration in the protoplanetary disk, many planet pairs that are locked in resonance have an increased libration amplitude due to the dissipation induced by the disk.

However, this new scenario still involves the tidal effect and should thus be very efficient for close-in systems, but not for the farthest ones. This is the main argument against the tidal dissipation scenario (e.g., Rein 2012; Baruteau & Papaloizou 2013), while the other proposed mechanisms (Rein 2012; Baruteau & Papaloizou 2013; Petrovich et al. 2013; Goldreich & Schlichting 2014; Chatterjee & Ford 2014; Xie 2014) are able to act both on close-in and farther systems. In the following we reanalyze the *Kepler* statistics with a focus on the distance of the planets to the star.

2. Dependency on the distance to the star

Different authors analyzed the impact of the distance to the star on the distribution of systems close to first-order mean-motion resonances. Rein (2012) divided the sample of *Kepler* planet pairs into two groups depending on the period of the innermost planet. The author used a threshold of five days and found a similar distribution for systems with $P_1 < 5$ d and for systems with $P_1 \geq 5$ d. Using a threshold of ten days, Baruteau & Papaloizou (2013) reached the same conclusion. Both studies discarded the scenario of a tidally induced distribution of the period ratio since according to this scenario, the excess should only be observed for the innermost systems.

In Fig. 2 we show the results of a similar study on more recent data (Q1-Q16 KOI catalog, Batalha et al. 2013). Our findings disagree with previous studies. We divided the data set into three groups:

1. close-in systems with $P_1 < 5$ d,
2. intermediate systems with 5d $\leq P_1 < 15$ d,
3. farthest systems with $P_1 \geq 15$ d.

For groups 1 and 2, we observe an excess of planets in external circulation (i.e., with a period ratio higher than the resonant value, $P_2/P_1 > (p+1)/p$ for the resonance $p+1$:p). However, the excess seems more significant for the closest systems (group 1). In addition, there is no detected close-in system (group 1) inside the resonance ($P_2/P_1 \approx (p+1)/p$), while a significant number of farther systems (groups 2 and 3) are found in commensurability. Moreover, the number of systems in commensurability in the third group is similar to or even higher than the number of pairs in external circulation.

[1] Lee et al. (2013) considered the same scenario of resonance departure at low eccentricities as in previous studies (Papaloizou & Terquem 2010; Papaloizou 2011; Lithwick & Wu 2012; Delisle et al. 2012; Batygin & Morbidelli 2013).

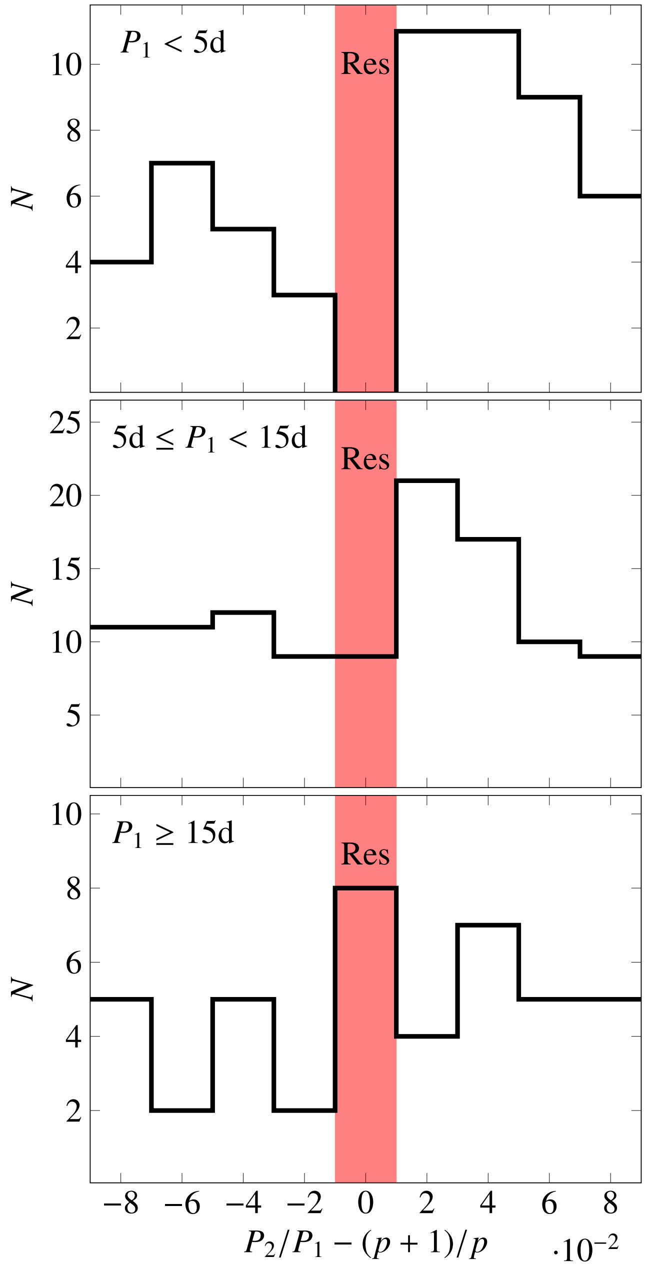

Fig. 2. Same as Fig. 1, but the statistics are computed using different subsets of KOI pairs depending on the period of the inner planet (P_1). We divide the data set into three groups: $P_1 < 5$ d (*top*), 5 d $\leq P_1 < 15$ d (*middle*) and $P_1 \geq 15$ d (*bottom*). See text for discussion.

Figure 3 shows cumulative distributions of the period ratio in the vicinity of the 2:1 and 3:2 mean-motion resonances for these three groups. The conclusions are the same as for Fig. 2. We performed K-S tests on the distributions given in Fig. 3 to check the statistical significance of the observed differences between the three distributions. The K-S test gives the probability of obtaining distributions at least as different as the observed ones with random samplings following the same underlying law. This probability is 0.08% for groups 1 and 3. It is thus very unlikely that both empirical distributions come from the same underlying law and are this different just by chance. When comparing the intermediate group (2) with the two extreme groups (1 and 3), the differences are of course less significant and the probabilities given by the K-S test are 3.5% (groups 1 and 2) and 10% (groups 2 and 3).

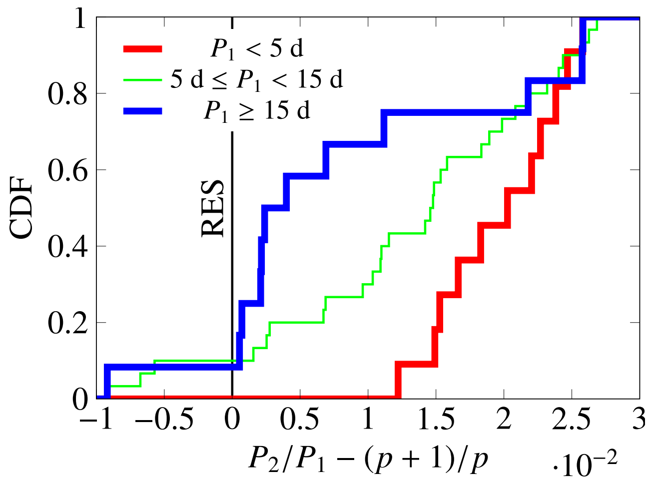

Fig. 3. Cumulative distributions of planet pairs in the vicinity of the 2:1 and 3:2 mean-motion resonances (the statistics of both resonances are accumulated) for the three groups defined in Fig. 2 (see also Sect. 2) Using K-S tests to compare these distributions, we obtain p-values of 0.08% (red and blue distributions), 10% (blue and green), and 3.5% (green and red). See text for discussion.

Therefore, we conclude that the distance to the star does have a statistically significant impact on the distribution of the period ratio of planet pairs. Very close-in systems ($P_1 < 5$ d) are not found in resonance and are very often found in external circulation, while for the farthest systems ($P_1 \geq 15$ d), both populations (commensurability and external circulation) are equivalent with a slight excess of systems in commensurability. While a strong dependency on the distance to the star arises naturally within the framework of tidal dissipation, the other possible mechanisms would require additional consideration to explain the data.

3. Conclusion

We showed that the distribution of the period ratio among pairs of planets depends on the distance of the planets to the star. For close-in systems no planet pair in first-order mean-motion resonances (2:1, 3:2) is detected, and there is an excess of planets in external circulation, that is close to the resonance, but with a period ratio higher than the resonant value. For the farthest systems, slightly more pairs are in commensurability than there are in external circulation. Using a K-S test to compare these two distributions, we obtained a p-value of 0.08% and conclude that the differences we observe are statistically significant. Some observational biases might contaminate the data sets, but it seems very unlikely that the differences we observe between close-in and farther systems arise from these biases. Tidal dissipation raised by the star on the planets naturally explains these observations because this effect strongly depends on the distance to the star and is much stronger for close-in systems.

These observations together with the new scenario of formation we proposed recently (still involving the tidal dissipation, but with a faster evolution of the period ratio, see Delisle et al. 2014, Sect. 5) favor a strong influence of tidal dissipation at the origin of the excess of planets in external circulation in the *Kepler* data.

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