Tidal dissipation and the formation of Kepler near-resonant planets

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July 25, 2014

ABSTRACT

Multi-planetary 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 these near-resonant systems were initially in resonance and reached their current configuration through tidal dissipation. The argument that has been opposed to this scenario is that it only applies to the close-in systems and not to the farthest ones for which the tidal effect is too weak. Using the catalog of KOI of the Kepler mission, we show that the distributions of period ratio among the most close-in planetary systems and the farthest ones differ significantly. This distance dependent repartition is a strong argument in favor of the tidal dissipation scenario.

Key words. celestial mechanics – planetary systems – 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 multi-planetary systems allows to test 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) whereas 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 period ratio of planet pairs close to these first-order resonances using the Q1-Q16 KOI catalog (Batalha et al. 2013).

This data set contains the Kepler confirmed planets as well as 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 involving 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), between planets and planetesimals (Chatterjee & Ford 2014), or in-situ formation (Petrovich et al. 2013; Xie 2013). In this article we provide some statistical clues in favor of the scenario involving tidal dissipation in planets 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 similar to the observed one is naturally produced by tidal dissipation raised in 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 \( \frac{P_2}{P_1} - (p + 1)/p \approx 2 \times 10^{-2} \) 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 of disappearing of the proto-planetary disk) is significant, the system is able to cross the separatrix and leave the resonance while the eccentricities of the planets are locked in first-order mean-motion resonances.

Fig. 1. Distribution of period ratio between pairs of planets close to the 2:1 and 3:2 mean-motion resonances. The distributions around both resonances are accumulated in order to obtain a more important 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 \( \frac{P_2}{P_1} < (p + 1)/p \) and positive values correspond to external circulation \( \frac{P_2}{P_1} > (p + 1)/p \). We observe an important excess of systems in external circulation, with \( P_2/P_1 - (p + 1)/p \approx 2 \times 10^{-2} \).
planets are still important \((e_1 \geq 0.15)\). 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 gets more efficient with increasing eccentricities (see Delisle et al. 2014, section 5). Therefore, many systems that were discarded by Lee et al. (2013) could actually have evolved from the resonance to their current configuration by tidal dissipation, following this new scenario. Supposing an important initial amplitude of libration in the resonance is not absurd. Goldreich & Schlichting (2014) showed that during the phase of migration in the proto-planetary disk, many planet pairs that are locked in resonance have their amplitude of libration increased by 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 opposed to the tidal dissipation scenario (e.g. Rein 2012, Baruteau & Papaloizou 2013). On the contrary, the other proposed mechanisms do not have an important dependency on the distance to the star. 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 already 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 in two groups depending on the period of the innermost planet. The author used a threshold at 5 days and found a similar distribution for systems with \(P_1 < 5d\) and for those with \(P_1 \geq 5d\). Using a threshold at 10 days, Baruteau & Papaloizou (2013) reached the same conclusion. Both studies discarded the scenario of a tidally induced distribution of period ratio since according to this scenario the excess should only be observed for the innermost systems.

In Fig. 1 we show the results of a similar study on more recent data (Q1-Q16 KOI catalog, Batalha et al. 2013). Our findings are in disagreement with previous studies. We divide the data set in three groups:

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

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). It is also important to notice that there is no detected close-in system (group 1) inside the resonance \((P_2/P_1 = (p + 1)/p)\) whereas a significant number of farther systems (groups 2 and 3) are found in resonance. Moreover, in the third group, the number of systems inside the resonance is comparable to or even higher than the number of pairs in external circulation.

Figure 2 shows cumulative distributions of 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. 1. We performed K-S tests on the distributions given in Fig. 2 in order to check the statistical significance of the observed differences between the three distributions. The K-S test give the probability to obtain distributions at least as different as the observed ones with random samplings following the same underlying law. This probability is of 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 both extreme ones (1 and 3), the differences are of course less significant and the probabilities given

\(^1\) 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. 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). The conclusions are the same as in Fig. 2 for farthest systems (blue); there is a pile-up of planets in the resonance, while for close-in systems (red) the pile-up is shifted toward higher values of the period ratio and we observe a lack of resonant systems. The distribution of intermediate systems (green) is, not surprisingly, intermediate. Using K-S tests to compare these distributions, we obtain a p-value of 0.08% for both extreme distributions (red and blue). The p-value for the blue and green distributions is 10%, and for the green and red ones 3.5%.

by the K-S test are respectively 3.5% (groups 1 and 2) and 10% (groups 2 and 3).

Therefore, we conclude that the distance to the star does have a statistically significant impact on the distribution of period ratios of planet pairs. Very close-in systems ($P_1 < 5\,\text{d}$) are not found in resonance and are very often found in external circulation, whereas for the farthest systems ($P_1 \geq 15\,\text{d}$), both populations (resonance and external circulation) are equivalent with a slight excess of systems inside the resonance. These observations are well explained by the tidal dissipation scenario of formation of Kepler near-resonant planets. On the contrary, the other proposed mechanisms do not predict this dependency on the distance to the star.

3. Conclusion

In this letter, we show that the distribution of period ratio among pairs of planets depends on the distance of the planets to the star. For close-in systems there is not any detected planet pairs in first-order mean-motion resonances (2:1, 3:2), and there is an excess of planets in external circulation, i.e. close to the resonance but with a period ratio higher than the resonant value. For the farthest systems, the number of resonant pairs is slightly greater than the number of planets in external circulation. Using a K-S test to compare both distributions, we obtain a p-value of 0.08% and conclude that the differences we observe are statistically significant. Tidal dissipation raised by the star on the planets naturally explains these observations because this effect has an important dependency on the distance to the star and is much stronger for close-in systems. Moreover, it is the only proposed mechanism of formation of these near-resonant systems that predicts such a strong dependency.

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) favor a large influence of tidal dissipation at the origin of the excess of planets in external circulation in the Kepler data.

Acknowledgements. We thank Stéphane Udry for useful advice. This work has been supported by PNP-CNRS, CS of Paris Observatory, and PICS05998 France-Portugal program.

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