

Period Ratio Distribution of Near-Resonant Planets Indicates Planetesimal Scattering

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Abstract. An intriguing trend among *Kepler*'s multi-planet systems is an overabundance of planet pairs with period ratios just wide of mean motion resonances (MMR) and a dearth of systems just narrow of them. In a recently published paper Chatterjee & Ford (2015; henceforth CF15) has proposed that gas-disk migration traps planets in a MMR. After gas dispersal, orbits of these trapped planets are altered through interaction with a residual planetesimal disk. They found that for massive enough disks planet-planetesimal disk interactions can break resonances and naturally create moderate to large positive offsets from the initial period ratio for large ranges of planetesimal disk and planet properties. Divergence from resonance only happens if the mass of planetesimals that interact with the planets is at least a few percent of the total planet mass. This threshold, above which resonances are broken and the offset from resonances can grow, naturally explains why the asymmetric large offsets were not seen in more massive planet pairs found via past radial velocity surveys. In this article we will highlight some of the key findings of CF15. In addition, we report preliminary results from an extension of this study, that investigates the effects of planet-planetesimal disk interactions on initially non-resonant planet pairs. We find that planetesimal scattering typically increases period ratios of non-resonant planets. If the initial period ratios are below and in proximity of a resonance, under certain conditions, this increment in period ratios can create a deficit of systems with period ratios just below the exact integer corresponding to the MMR and an excess just above. From an initially uniform distribution of period ratios just below a 2:1 MMR, planetesimal interactions can create an asymmetric distribution across this MMR similar to what is observed for the *Kepler* planet pairs.

Keywords. scattering, methods: n-body simulations, methods: numerical, planets and satellites: general, planetary systems, planetary systems: protoplanetary disks

1. Introduction

NASA's *Kepler* mission has revolutionized our understanding of planetary systems, their occurrence rate, multiplicity and physical properties. One trend apparent among this new class of small planets was a-priori quite unexpected from traditional theories; there is a statistically significant excess of planet pairs with period ratios slightly wide of first order mean motion resonances such as 2:1 and 3:2, and a dearth of them just narrow of these resonances (Lissauer *et al.* 2011, Fabrycky *et al.* 2014, Steffen & Hwang 2015; Figure 1). Interestingly, this trend is absent in planets that were previously discovered

via radial velocity (RV) surveys (e.g., Butler *et al.* 2006). Smooth gas-disk migration can trap planets in MMRs. However, such resonant planets are expected to have period ratios with very small offsets from the integer ratio corresponding to the MMR, $\epsilon \equiv P_2/P_1 - (j+1)/j \sim \pm 10^{-3}$. Indeed, adjacent planet pairs discovered via past RV surveys show period ratio distribution with a distinct excess at the expected period ratio for the 2:1 MMR with very small ϵ , consistent with the expectations from smooth gas-disk driven migration (Lee & Peale 2002, Butler *et al.* 2006, Armitage 2013). In contrast, the near-resonant *Kepler* planet pairs are likely not in actual resonance (Veras & Ford 2012). Nevertheless, the overall close to uniform distribution away from resonance, and the mysterious asymmetric abundance across MMRs, such as 2:1 and 3:2, indicate that the *Kepler* planet pairs somehow knew about these resonances. However, some other process has driven them wide of the resonance and created this asymmetry. Planet-planet scattering can break resonances, however, they bring dramatic changes in the planetary orbits, often making them highly eccentric, which is inconsistent with the multi-transiting architecture of the *Kepler* systems (e.g., Ford & Rasio 1996, Chatterjee *et al.* 2008). The large ($\epsilon \sim 10\%$) positive offsets in the near-resonant planet pairs observed by *Kepler* thus has generated a lot of interest.

It is generally believed that these planets were initially trapped in a MMR. Subsequently, some dissipative process drove them wide of their initial period ratios. The most likely dissipative mechanism responsible for the observed trend is still a matter of debate. The proposed dissipative mechanisms include dissipation from tide (Lithwick & Wu 2012, Batygin & Morbidelli 2013, Delisle & Laskar 2014), turbulence in protoplanetary disk (Rein 2012), and scattering with a planetesimal disk (Moore *et al.* 2013; CF15). Although, the most well studied, the tidal dissipation mechanism is also the most debated. Lee *et al.* (2013), Silburt & Rein (2015) argue that even under generous assumptions, the large observed positive ϵ for most *Kepler* planet pairs near a MMR cannot be explained by tides alone. It was also suggested that in-place mass growth of a planet via planetesimal accretion can lead to formation of an over density of particles just wide of a MMR (Petrovich *et al.* 2013). However, planetesimal accretion typically lead to migration of the planet making the in situ growth assumption questionable. It was also suggested that the observed period ratio distribution may be explained due to overstable libration of the *Kepler* planets due to gas-disk driven migration coupled with eccentricity damping (Goldreich & Schlichting 2014). However, Hands *et al.* (2014), Deck & Batygin (2015) present an opposing view.

In this article, we will focus on planet-planetesimal disk interactions as the mechanism for the observed asymmetric period ratio distribution across 2:1. Planet-planetesimal disk interactions have been well studied in other contexts, especially for the outer Solar system, and is generally believed to be a natural consequence of the core-accretion paradigm of planet formation (e.g., Fernandez & Ip 1984, Ida *et al.* 2000, Gomes *et al.* 1004, Kirsh *et al.* 2009). In §2 we will briefly describe our numerical setup. In §3 we will highlight our key results. First, we will highlight the findings of CF15 with some additional details. We will also present results from new simulations involving interactions of initially non-resonant planets with a planetesimal disk. Finally, in §4 we will summarize our results and discuss the implications.

2. Numerical Setup

The simulations presented in this article are from two distinct sets. One investigates the effects of planetesimal scattering on the orbits of two planets initially trapped in a 2:1 MMR (CF15). We call this **Set 1**. The other investigates the effects of planetesimal

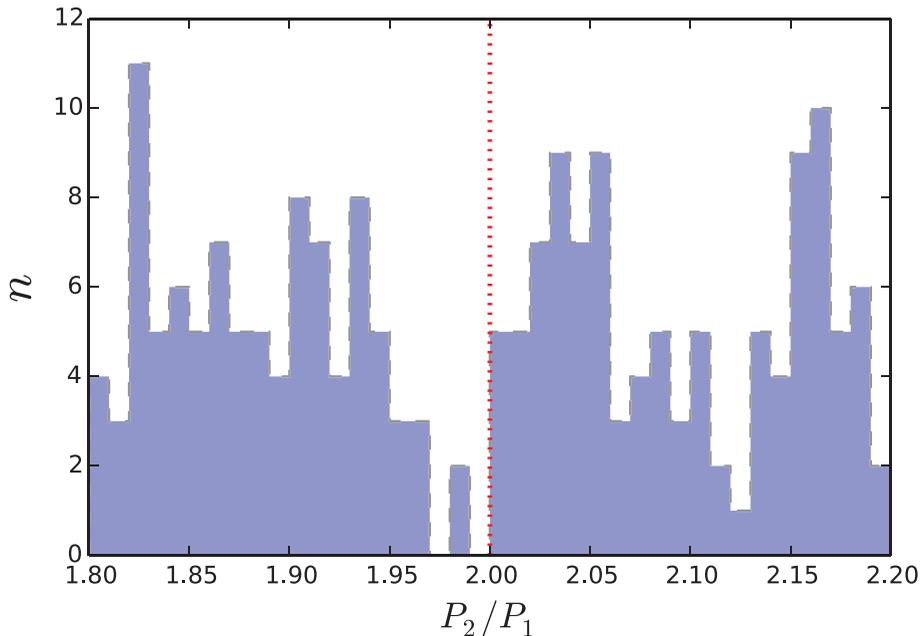


Figure 1. Period ratio distribution of adjacent planet pairs discovered by *Kepler* close to the period ratio expected for a 2:1 MMR. There is a dearth of systems with period ratios just narrow of the resonance and an excess of systems just wide of the resonance. The vertical (red-dotted) line shows the exact position of a period ratio of 2. *Kepler* data was extracted from NASA’s exoplanet archive.

scattering on planet orbits that are not initially trapped in 2:1 MMR but, are just narrow of the MMR. We call this **Set 2**.

The details of the numerical setup for **Set 1** are described in CF15. However, for completeness, we will briefly describe the key aspects. In general, the physical picture we have in mind is that while a gas disk is present, gas-disk interactions may trap two planets into 2:1 MMR. Once the gas disk is depleted, the resonant planets can freely interact with a residual planetesimal disk. We are interested in the effects of the latter interactions. Thus, we are interested in a system that initially was dissipative and transitions into a N -body. Ideally, planets, planetesimals, and a gas disk should be modeled together with all physics included, however, this full problem is computationally impractical. Hence, we generate plausible initial conditions for the stage of planet-planetesimal disk interactions in two steps. First, we use an analytic \dot{a} and \dot{e} prescription to trap two planets in 2:1 MMR (Lee & Peale 2002). Second, we create planetesimal orbits consistent with the presence of the planets in the following way. The structure of the residual planetesimal disk after gas-disk depletion is uncertain. Nevertheless, we use planetesimal disk profiles described by $d\Sigma/da \propto a^\alpha$, where Σ and a are the surface density and distance from the star for the planetesimals, respectively. At the epoch of gas disk depletion, the planetesimal disk profile would not remain a simple power-law. Instead, the planets would alter the planetesimal disk densities near them by dynamically scattering or accreting some of the nearby planetesimals that are on orbits unstable even with the stabilization provided by dissipation from a gas disk (e.g., Matsumura *et al.* 2010). To imitate this effect we embed the resonant planets in a planetesimal disk with a power-law profile given by $d\Sigma/da \propto a^\alpha$. We treat all planetesimals as test particles. We let the planets alter the disk for at least $\sim 10^2$ orbits of the outer planet. We collect the properties of the planetesimals that

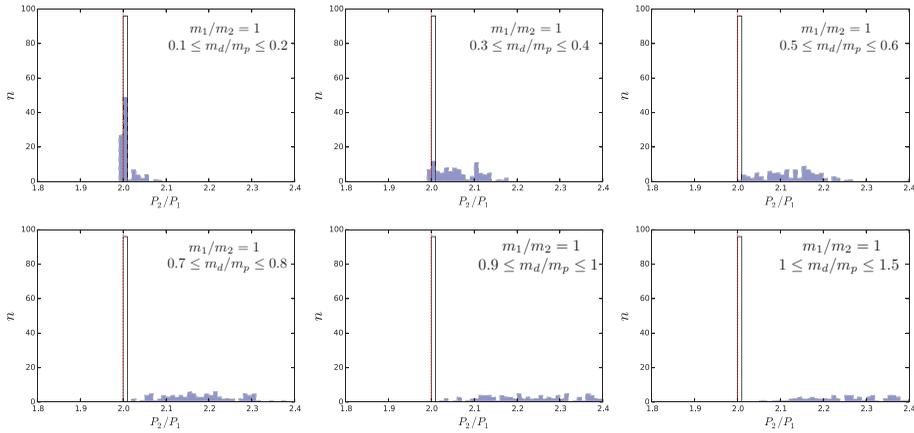


Figure 2. The initial (black) and final (blue filled) period ratio distributions for models with equal mass planets and planetesimal disk profile given by $\alpha = -3/2$ (a subset of models presented in CF15). Each panel shows results from models with a different m_d/m_p value, listed in each panel. In all cases, the planet pairs are initially trapped in a 2:1 MMR. As a result, the initial period ratios are always close to 2. Depending on m_d/m_p the final period ratio distribution changes. For $m_d/m_p < 0.3$ resonance is not broken for most planet pairs. As m_d/m_p increases, so fraction of systems for which resonance is broken and the highest ϵ attained, both increase.

survive this phase and create a database of allowed planetesimal orbits for each planet pair. We call this the clean-up stage. We randomly choose 2×10^3 orbits from this database, assign masses to the planetesimals according to the assumed planetesimal disk mass to planet mass ratio. We evolve the resonant planets with the planetesimals until the period ratio of the planets' orbits stop changing ($\sim 10^5$ years). CF15 has varied the planetesimal disk profile by changing the power-law index α between -2.5 to 3, planet-planet mass ratios m_1/m_2 between 0.1 to 10, and the planetesimal disk to planet mass ratio ($m_d/(m_1 + m_2) \equiv m_d/m_p$) between 0.1 to 1.5.

We have started investigating the effects of a residual planetesimal disk on initially non-resonant planets. In this set, **Set 2**, we closely follow the prescriptions of CF15 summarized above. However, we choose planet pairs with initial orbits such that the initial period ratio is between 1.8 and 2, just narrow of the 2:1 MMR. The inner planet's semimajor axis is kept at $a_1 = 0.1$ AU, a typical value for the *Kepler* planets. We generate 50 systems such that the period ratio P_2/P_1 is between 1.8 and 2. The eccentricities of the planets' orbits are drawn from a Rayleigh distribution with scale 0.005 (e.g. Hadden & Lithwick 2014). The orbital inclinations (I) are drawn uniformly in $\cos I$ with I between -0.1 and 0.1° . Planets have equal mass and are equal to the mass of Neptune (M_N) and have Neptune-like densities. For each pair of planetary orbits created this way, we generate 4 random realizations varying the phase angles in their full range. The initial planetesimal disk profile is given by $d\Sigma/da \propto a^{-3/2}$. The planetesimal disk edges are set at orbits with period $P_1/3$ and $3P_2$. For each planet pair, we perform the initial cleaning up of planetesimals exactly the same way as prescribed by CF15. For each case, a database of orbits is generated. We randomly select 2×10^3 orbits and give each planetesimal a mass $m_{pl} = 1 \times 10^{-3} M_N$, such that $m_d/m_p = 1$. We integrate the planet-pair and planetesimals using the Bulirsch-Stoer integrator included in Mercury (Chambers 1999). We stop our integrations at 2×10^4 year, equivalent to $\approx 6 \times 10^5$ of the inner planet's initial orbital period. We confirm that the majority of the planetesimal interactions happen much earlier than our chosen integration stopping time.

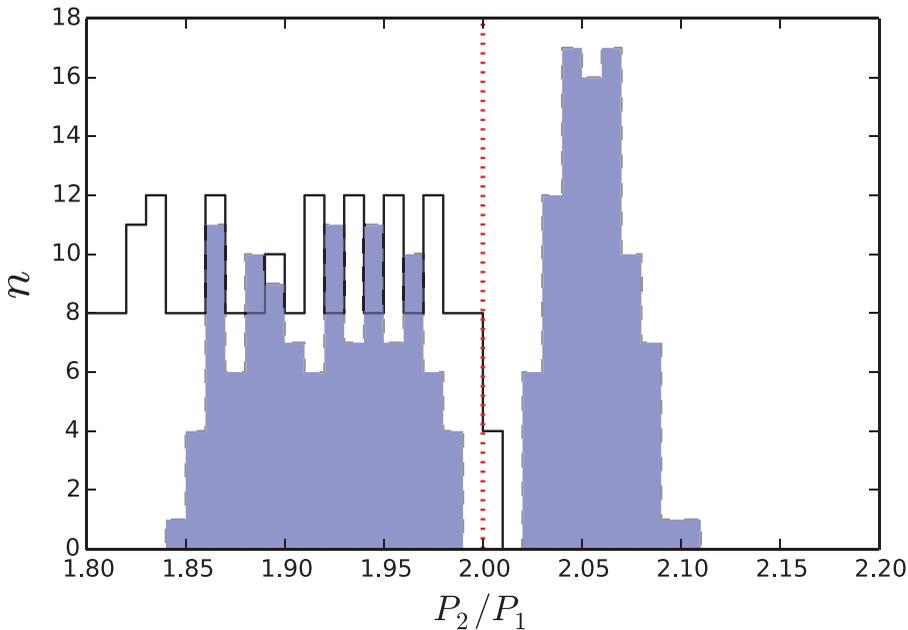


Figure 3. Initial (black) and final (blue filled) period ratio distributions for the set of simulations including initially non-resonant planets and a planetesimal disk (Section 2). Initially $m_1/m_2 = 1$, $\alpha = -3/2$, and $m_d/m_p = 1$. As a result of planetesimal interactions the period ratios generally increase. As the pairs approach 2:1 MMR from the inside, the resonance is skipped and the period ratio increases to a value > 2 . Thus, a dearth of planet pairs with period ratios just smaller than 2 and an excess of pairs with period ratios just higher than 2 are created.

3. Results

CF15 has investigated the effects of planetesimal interactions on the orbits of planet pairs initially trapped in a 2:1 MMR. The key results of CF15 are as follows. If the total mass of planetesimals that had strong interactions with the planets is high enough to break resonance, then planet-planetesimal interactions naturally increase the period ratio. The final offset from the MMR depends strongly on the ratio of the total mass of planetesimals that interacted with the planets and the planet mass. When resonance is broken, offset ϵ can have large positive values. If the resonance is not broken due to insufficient mass in nearby planetesimals, ϵ remains small ($\sim 10^{-3}$) and can have both positive or negative values. As a result, it is easier to break resonance and create large positive ϵ for low-mass planet pairs typical of those discovered by *Kepler*, compared to the much higher mass planet pairs discovered via past RV surveys. Figure 2 shows the initial and final period ratio distribution from a subset of simulations presented in CF15. As the ratio m_d/m_p increases, so does the fraction of systems where the resonance is broken and also the value of the highest ϵ the planet pairs can attain.

CF15 results suggest that planetesimal interactions with resonant planet pairs can naturally redistribute these planet pairs wide of the initial resonance. However, CF15 do not directly address the dearth of planet pairs with period ratios just narrow of 2:1. We have started a systematic study of the effects of planetesimal scattering on planet pairs that are initially not in resonance, rather has period ratios slightly smaller than 2 (Set 2). This is equivalent to a scenario where planet pairs do not go through significant migration in a gas disk. Thus, period ratios below and up to 2 are populated uniformly before planetesimal scattering can take place. Figure 3 shows the initial and final period ratio

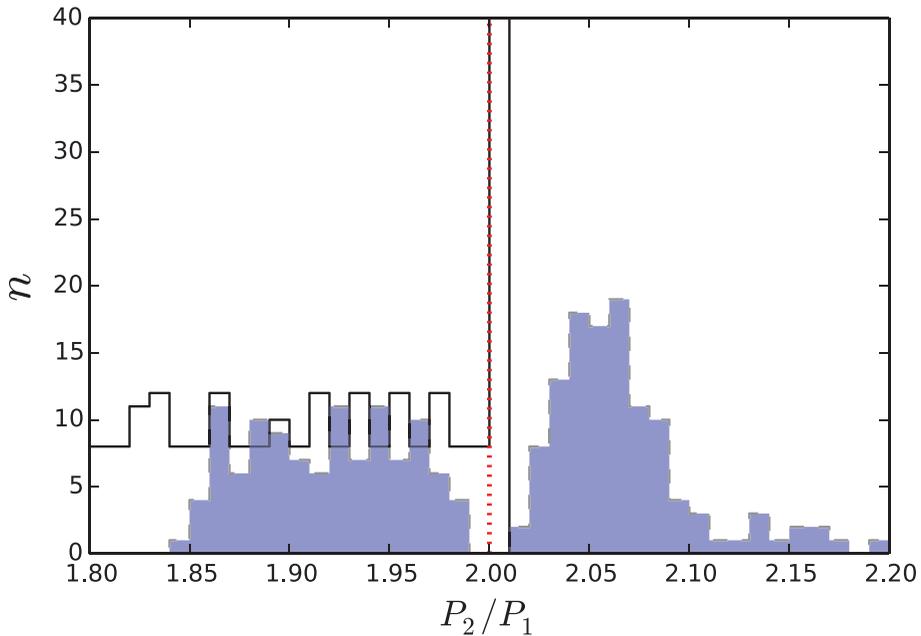


Figure 4. The same as Figure 3 but combining models from CF15 with $m_1/m_2 = 1$, $\alpha = -3/2$, and $m_d/m_p \geq 0.3$ and those from **Set 2** (§2).

distributions for a large (2×10^2) set of simulations, each involving two planets and 2×10^3 planetesimals (§2). Initially, the planet pairs have period ratios uniformly spaced between 1.8 and 2. Interactions with planetesimals from the disk generally increase the period ratios. Interestingly, as some of the planet pairs approach the 2:1 MMR via planetesimal driven divergent migration, they tend to skip the resonance and get deposited wide of the resonance. As a result, a dearth of systems is created with period ratios slightly below 2 and an excess of systems is created with period ratios slightly above 2.

In Figure 4 we combine the models from CF15 with $m_1/m_2 = 1$, $\alpha = -3/2$ and $m_d/m_p \geq 0.3$ with those from **Set 2**. Although the relative initial abundances between initially resonant and non-resonant planets is somewhat ad-hoc, the combined period ratio distribution is qualitatively very similar to what is observed across the 2:1 MMR for *Kepler*'s adjacent planet pairs. Hence, immediately after gas disk dispersal, if planet pairs have period ratios distributed uniformly below 2:1 with some excess of pairs at 2:1, and there is sufficient mass in nearby planetesimals in a residual planetesimal disk, then after planetesimal interactions the final period ratio distribution will, at least qualitatively, be very similar to what is observed of the *Kepler* planet pairs near 2:1 (Figure 1).

4. Discussion

In this article we summarize the key results of CF15. In addition, we present preliminary results from a new set of simulations with initially non-resonant planets and a planetesimal disk. Our results suggest that planetesimal scattering may be responsible for both the excess of planet pairs just wide of the 2:1 MMR and the dearth of systems just narrow of it.

We made several simplifying assumptions in this article. For example, in the new set of simulations with non-resonant planet pairs, we assume that the initial period ratios are distributed uniformly below 2 and all the way up to 2. This of course is not necessarily

true in reality. Sufficiently far away from a MMR the period ratios of *Kepler's* planet pairs appear to be random. However, they may not have been so immediately after gas disk dispersal. In reality, there may have been a dearth of systems just narrow of a MMR simply because some systems, while migrating within a gas disk, got trapped into the MMR. In that sense, our assumption of uniform period ratio distribution below the 2:1 MMR is the most conservative one. Even if after gas disk dispersal the period ratios are uniformly distributed narrow of the 2:1 MMR, planetesimal scattering from a sufficiently massive disk can create a dearth of systems with period ratios just below 2. These systems, in turn, pile up with period ratios slightly above 2. Encouraged by our preliminary results, we are exploring this problem more thoroughly by covering a larger parameter space and obtaining a more detailed understanding of the evolution of the planet pairs as they cross the 2:1 MMR from inside out via planetesimal driven migration.

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Questions and Comments:

QUESTION: In your simulations you have ignored planetary migration. If the planets migrate in a gas disk it will clear a larger gap in the planetesimal disk. As a result, after gas dispersal there won't be many planetesimals near the planets and interactions will be rare. Can you comment on that?

CHATTERJEE: Indeed, planets would migrate in a gas disk. So would the planetesimals. In fact, the planetesimals are expected to migrate faster than the planets. As a result, following gas dispersal, the surface density of planetesimals may be enhanced exterior to the planets. That is why we considered a wide variety of planetesimal surface density profiles, including those for which the surface density increases with the distance from the star.

Of course, the ideal way to study this problem is to simulate gas disks, planets, and planetesimals all together including all relevant physical effects. Such simulations are unfortunately numerically impractical. Hence we are forced to adopt a scheme that mimics the expected configuration of a system that was dissipative initially and then became pure N -body. In particular, we constructed our initial conditions in two steps, first trapping planets in resonance, and then removing planetesimals that would be unstable on short timescales. We believe that this could mimic the configuration of planets and planetesimal disks at the epoch of gas dispersal, at least qualitatively. A larger gap in planetesimals would slow down subsequent interactions with the planets, but as long as there are enough planetesimals to interact with the planets, the planetary orbits will diverge leading to a ratio of orbital periods greater than that of the exact resonance. Given that the general outcome of planet-planetesimal interactions is unchanged for the wide range in explored planetesimal disk properties, we believe that the details of planetesimal disk structures are unlikely to change our results qualitatively.