THE DESTRUCTION OF INNER PLANETARY SYSTEMS DURING HIGH-ECCENTRICITY MIGRATION OF GAS GIANTS

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ABSTRACT
Hot Jupiters are giant planets on orbits of a few hundredths of an AU. They do not share their system with low-mass close-in planets, despite the latter being exceedingly common. Two migration channels for hot Jupiters have been proposed: through a protoplanetary gas disk or by tidal circularization of highly eccentric planets. We show that highly eccentric giant planets that will become hot Jupiters clear out any low-mass inner planets in the system, explaining the observed lack of such companions to hot Jupiters. A less common outcome of the interaction is that the giant planet is ejected by the inner planets. Furthermore, the interaction can implant giant planets on moderately high eccentricities at semimajor axes < 1 AU, a region otherwise hard to populate. Our work supports the hypothesis that most hot Jupiters reached their current orbits following a phase of high eccentricity, possibly excited by other planetary or stellar companions.

Key words: planets and satellites: dynamical evolution and stability – stars: individual (Kepler-18, Kepler-23, Kepler-58, Kepler-339)

1. INTRODUCTION

Hot Jupiters were among the first exoplanets to be discovered (Mayor & Queloz 1995). However, their origin is still not understood, and models for their migration history fall into two categories: “Type II” migration at early times through the protoplanetary gas disk (Lin et al. 1996; Ward 1997); and migration at late times as planets’ eccentricities are excited by gravitational scattering in packed multi-planet systems (Rasio & Ford 1996; Chatterjee et al. 2008) or by secular perturbations from more distant planetary or binary companions (Yu & Murray 2003; Wu & Lithwick 2011; Beaugé & Nesvorný 2012; Petrovich 2015b, 2015a). High-eccentricity migration may better explain the observed misalignments between stellar spin and planetary orbits (Triaud et al. 2010; Winn et al. 2010; Wu & Lithwick 2011; Beaugé & Nesvorný 2012; Storch et al. 2014) as well as the innermost semimajor axes of the bulk of the hot Jupiter population (Ford & Rasio 2006; Plavchan & Bilinski 2013; Valsecchi & Rasio 2014). A requirement of this channel is that hot Jupiters have (or had in the past) planetary or stellar companions on wide orbits, and indeed recent studies estimate that around 70% of hot Jupiters have companion giant planets or stars on wide orbits (Knutson et al. 2014; Ngo et al. 2015).

On the other hand, hot Jupiters are not found to have low-mass, close-in companions. No such companions have yet been found by radial-velocity (RV) surveys, while survey results from the Kepler spacecraft found no evidence of additional transiting companions or transit timing variations in hot Jupiter systems (Steffen et al. 2012); this deficit was statistically significant compared to multiplicities of warm Jupiter and hot Neptune systems. Nor have ground-based searches for companions that may cause strong transit timing variations proved fruitful (e.g., Hoyer et al. 2012; Maciejewski et al. 2013), despite their sensitivity to Earth-mass companions in mean motion resonance with a hot Jupiter. However, low-mass planets on close orbits are extremely common around stars that do not host hot Jupiters: results from Kepler transit photometry show that 52% of stars have at least one planet with $P < 85$ days and $R_{pl} > 0.8 R_J$ (Fressin et al. 2013), while RV surveys similarly show that 23% of stars host at least one planet with $P < 50$ days and $m_{pl} > 3 M_J$ (Howard et al. 2010). Furthermore, such planets often occur in multiple systems: the statistics of Kepler candidate multiplicities requires a significant contribution from multi-planet systems (Lissauer et al. 2011; Fang & Margot 2012; Fressin et al. 2013). In many systems, then, migrating giant planets that will become hot Jupiters will interact with formed or forming systems of low-mass planets.

The lack of close companions to hot Jupiters can help to distinguish the different migration modes (Steffen et al. 2012). Simulations show that a giant planet migrating through an inner gas disk to become a hot Jupiter does not necessarily suppress planet formation in the inner disk (Mandell & Sigurdsson 2003; Fogg & Nelson 2005, 2007a, 2007b, 2009; Mandell et al. 2007), while embryos migrating after the giant form a resonant chain behind it and may accrete into a planet of detectable size (Ketchum et al. 2011; Ogihara et al. 2013, 2014).

In contrast, we show in this paper that during high-eccentricity migration, the giant planet almost always destroys all low-mass planets on orbits of a few tenths of an AU. Previous studies have shown that scattering among multiple giant planets can clear out material in the terrestrial planet region around 1 AU through direct scattering (Veras & Armitage 2005, 2006) or secular resonance sweeping (Matsumura et al. 2013), and that it can suppress terrestrial planet formation in this region (Raymond et al. 2011, 2012). We choose to focus our attention on very close-in systems more relevant for comparison to Kepler observation (~0.1 AU), which may have significant mass in inner planets (up to ~40 $M_{Earth}$ in total). We further consider the general case of a highly eccentric giant planet, which may represent the outcome of scattering but which may also arise through other eccentricity excitation mechanisms such as Kozai perturbations or other secular effects.

In Section 2 of this paper we briefly review the population of planet candidates revealed by the Kepler spacecraft. In Section...
we describe the numerical approach we take to study the interaction of eccentric giant planets with close-in inner planets. In Section 4 we present the results of our numerical integrations. We discuss our findings in Section 5, and conclude in Section 6.

2. PLANETARY MULTIPLICITIES

We show the multiplicities of the population of Kepler planet candidates by taking the catalog of Kepler Objects of Interest (KOIs) from the Q1 to Q16 data release at the NASA Exoplanet Archive (NEA) http://exoplanetarchive.ipac.caltech.edu/ (release of 2014 December 18; accessed 2015 January 08). This provided a list of 7348 planet candidates. KOIs may be genuine planets or false positives, with false positive probabilities up to 1 in 3 in some regions of parameter space (Santerne et al. 2012; Coughlin et al. 2014). Moreover, parameters for some planets in the NEA are unphysical. We therefore performed several cuts on this list to attempt to remove false positives and poorly characterized candidates. No FPs: Removal of any candidate classed as a false positive in the NEA (in either of the columns “disposition using Kepler data” or “Exoplanet Archive disposition”). 5739 candidates. $L + 11$: Following Lissauer et al. (2011), we consider only planets with SNR > 16, $P < 240$ days and $R < 22.4R_\odot$, thus ensuring completeness and removing candidates with unphysically large radii. 3678 candidates. $L + 11$ and no FPs: Applies the cuts from Lissauer et al. (2011), and also removes any false positives identified in the NEA Q1–Q16 data. 3228 candidates. NEA good: Removes NEA-identified false positives, and furthermore only includes planets that are listed as “confirmed” or “candidate” in at least one of the disposition columns, ensuring that the planets, if not confirmed, have passed some vetting to ensure a low probability of a false positive. 2052 candidates. Plots of planet radius versus period for these four samples are shown in Figure 1, where the contrast between solitary hot Jupiters and sociable low-mass planets is apparent. Although the numbers of single versus multiple systems vary (in particular, the NEA good sample has many multiples, as it is heavily influenced by the validation of numerous multiple-candidate systems by Rowe et al. (2014)), for our purposes the key observation is that hot Jupiters at the top left of the plot are single. We do see some candidate hot Jupiters with companions, but these detections are not robust. For example, with the $L + 11$ and $L + 11$ and no FPs cuts, we find KOI-199.01 and KOI-199.02. The latter component is marked as a background eclipsing binary in the Q1–Q6 data from the NEA. In the NEA good sample, we find KOI-338, confirmed by Rowe et al. (2014) as Kepler-141. This object has an unphysically large stellar radius in the NEA, measuring $19R_\odot$, larger than each of its planets’ orbital radii. Rowe et al. (2014) assign a radius of $0.8R_\odot$, reducing the radii of the planet candidates proportionately. Hence, we do not consider either of these potential exceptions to our assertion that hot Jupiters are single to be reliable. We adopt the $L + 11$ and no FPs sample as the most reliable. This has 3228 planet candidates, forming 2136 single-planet systems, 282 doubles, 109 triples, 31 quadruples, 13 quintuples, and 2 sextuples. We restrict attention to the triples and lower multiplicities as they offer better statistics.

3. NUMERICAL METHOD

3.1. N-body Model

We conduct an extensive ensemble of $N$-body integrations with the Mercury package (Chambers 1999). We consider a highly eccentric giant planet interacting with systems of three low-mass planets at $\sim0.1$ AU, chosen from among Kepler triple-candidate systems, assuming that the three transiting planets are the only ones present in the inner system. Our systems are representative of the range of planet sizes of the multi-planet Kepler systems (Figure 1). Integrations are run for 1 Myr.

We adopt the Bulirsch-Stoer algorithm with an error tolerance of $10^{-12}$. Within the 1 Myr integration duration, energy conservation is generally good; we reject a small number of runs with $\Delta E/E > 10^{-3}$. Collisions between bodies are treated as perfect mergers, and we consider a planet ejected from the system if it reaches a distance of 10,000 AU from the star. The code does not incorporate general relativistic corrections, but this is unimportant as the dynamics is dominated by scattering.

For our main integration runs, we take three-planet systems from the Kepler triples and add to the system a highly eccentric giant planet with a small pericenter. Our exemplar Kepler systems are Kepler-18, Kepler-23, Kepler-58, and Kepler-339. Kepler-18, -23, and -339 all have planets with orbits from $\sim0.05$ to $\sim0.12$ AU, and span the range of planetary radii of the Kepler multiple systems. Kepler-58 has planets on somewhat wider orbits, 0.09–0.23 AU. These systems are marked in the space of Kepler candidates in Figure 1.

The Kepler photometry allows a direct determination only of planet radii, but masses are more significant dynamically. Where available, we have taken masses determined by transit timing variations or radial velocities. Where these are unavailable, we have estimated masses based on a mass–radius or density–radius relation (Weiss & Marcy 2014). System parameters used for the simulations are given in Tables 1 and 2.

For each of these systems, we conducted integration suites with different properties of the giant planet. For all four systems, we conducted integrations with the giant’s initial semimajor axis of 10 AU, while for Kepler-18 and -339 we also conducted integrations starting at 1.25 AU. Within each combination of system and semimajor axis, we conducted 21 sets of 256 integrations, one set for each pericenter value $q$ from 0.01 to 0.20 AU in steps of 0.01 AU, and a final set at 0.25 AU (see Figure 3). Within each set, half of the giants were on prograde and half on retrograde orbits; within each subsample, the orientation of the orbit was isotropic in the respective hemisphere. The giant was always released from apocenter. The giant’s mass and radius were set to Jupiter’s values. Our setup assumes that during the initial excitation of the giant planet’s eccentricity, there is no effect on the inner system, a reasonable assumption (for example, a tightly packed system of planets protects itself against the Kozai effect; Innanen et al. 1997).

For the inner systems, we assigned the planets initially circular orbits with inclinations of up to $5^\circ$ from the reference plane, giving a maximum mutual inclination of $10^\circ$ with the distribution peaking at around $3^\circ.5$ (Johansen et al. 2012). We conducted an additional integration suite for the Kepler-18 system starting from a highly coplanar configuration of inner planets (inclinations up to $0^\circ.001$), finding little impact on the
outcome. The initial orbital phases of the inner planets were randomized. We conducted some integrations without giant planets to verify that our three-planet systems do not destabilize themselves on relevant timescales. No unstable systems were found over 1 Myr (128 runs for each Kepler triple studied).

We also conduct some ancillary integrations to test the effects of the relative orbital energies of the inner planets and the giant planet on the probability of ejecting the giant. All of these integrations were performed with a semimajor axis of 10 AU and a pericenter of 0.02 AU for the giant. We tested two hot Jupiter systems (51 Pegasi, Mayor & Queloz 1995; Butler et al. 2006; and HAT-P-7, Pál et al. 2008) and one high-multiplicity system discovered by radial velocity (τ Ceti; Tuomi et al. 2013). We also conducted additional integrations for Kepler-18 with the giant’s mass set to 0.1, 0.3, and 3$M_J$ at 10 AU, and with the giant’s mass set to 1$M_J$ at 5 and 2.5 AU. The ejection fractions from these integrations are used in the

![Figure 1. Periods and radii of candidate Kepler single-, double-, and triple-transit systems, with various selection criteria. (A): No FPs—known false positives removed; (B): $L + H$—cuts on radius, SNR, and period applied following Lissauer et al. (2011); (C): $L + H$ and no FPs—Lissauer et al. (2011) cuts applied and false positives removed; (D): NEA good—only retains those candidates confirmed or with favorable vetting. See the text for further details. Hot Jupiters are alone in systems, in contrast to both smaller planets and giant planets at longer orbital periods. We adopt the $L + H$ and no FPs selection as the most reliable. We mark the triple-candidate systems selected for our N-body integrations in blue, with their Kepler numbers shown.](image)

| Name          | $M_\ast/M_\odot$ | $R_\ast/R_\odot$ | Reference |
|---------------|------------------|------------------|-----------|
| Kepler-18     | 0.972            | 1.108            | 1         |
| Kepler-23     | 1.11             | 1.52             | 2         |
| Kepler-58     | 0.95             | 1.033            | 3         |
| Kepler-339    | 0.902            | 0.802            | 4         |

References. (1) Cochran et al. (2011), (2) Ford et al. (2012), (3) Steffen et al. (2013), (4) Rowe et al. (2014).

| Name          | $a$/AU            | $M_{pl}/M_\oplus$ | $R_{pl}/R_\oplus$ | Reference |
|---------------|-------------------|-------------------|-------------------|-----------|
| Kepler-18b    | 0.0477            | 6.9$^a$           | 2.00              | 1         |
| Kepler-18c    | 0.0752            | 17.3              | 5.49              | 1         |
| Kepler-18d    | 0.1172            | 16.4              | 6.98              | 1         |
| Kepler-23b    | 0.0749            | 4.86$^a$          | 1.89              | 2         |
| Kepler-23c    | 0.0987            | 8.05$^a$          | 3.25              | 2         |
| Kepler-23d    | 0.125             | 5.60$^a$          | 2.20              | 2         |
| Kepler-58b    | 0.0909            | 18.0              | 2.78              | 3         |
| Kepler-58c    | 0.1204            | 17.5              | 2.86              | 3         |
| Kepler-58d    | 0.2262            | 7.33$^a$          | 2.94              | 4         |
| Kepler-339b   | 0.0551            | 3.76$^a$          | 1.42              | 4         |
| Kepler-339c   | 0.0691            | 1.74$^a$          | 1.15              | 4         |
| Kepler-339d   | 0.0910            | 1.86$^a$          | 1.17              | 4         |

Note. $^a$ Mass is not measured directly: estimated from a mass–radius or density–radius relation (Weiss & Marcy 2014).

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product swallows planet b, leaving a single inner planet in the system after ejection of the eccentric giant. After 40 kyr, the giant is kicked onto a very wide orbit, only completing a few more orbits before acquiring a hyperbolic orbit at around 27 kyr. Meanwhile the c planet, which has enriched cores (e.g., Guillot et al. 2006). After evolving our surviving giant planets under tidal forces, we find that giants that have accreted one or more inner planets are more likely to become hot Jupiters than those that have not, although the relative infrequency of collision means that most of the hot Jupiters we form have not accreted other planets (Table 3). Due to the extreme collision velocities at these small orbital radii, the giant’s radius may be inflated by colliding with a smaller planet (Ketchum et al. 2011), while the impact velocity when two smaller planets collide can be several times their escape velocity, meaning that collisions may generate copious debris (Leinhardt & Stewart 2012). The inclination of the giant planet with respect to the inner planets does not have a strong effect on the outcome, although with a retrograde giant the fraction of destroyed inner planets colliding with the giant rather than the star rises slightly, as does the number of coexisting systems when the initial $q < 0.10$ AU. While the ejection of a Jovian planet by Neptune-sized ones may seem surprising, the ratio of ejections of the incoming giant to destruction of the inner planets can be understood in terms of the orbital energies of the two components (Figure 5): as the orbital energy of the giant is decreased (whether through lower mass or through higher semimajor axis), ejection becomes more likely. Planets scattering from near-circular orbits at semimajor axes of $\sim 0.1$ AU would be in a regime favoring collisions, as their physical radius is a significant

discussion of the effects of orbital energy on ejection probability (see Section 4), but their statistics are not otherwise discussed.

3.2. Tidal Model

Although we do not incorporate tidal forces into our N-body integrations, we post-process the planets surviving at the end of the 1 Myr N-body integration to follow their orbital evolution under tidal forces. To model the tidal evolution of the planets after the interaction between the giant and the inner planets has concluded, we use the simple “constant $Q$” model in the form given in Dobbs-Dixon et al. (2004). We include only the planetary tide, which is the most important for the planets’ eccentricity decay until the host star leaves the main sequence (Villaver et al. 2014). We adopt values for the planets’ tidal quality factors of $Q_{pl} = 10^6$ for the giants, $Q_{pl} = 10^5$ for the “Neptunes” Kepler-18c, d and their merger products, and $Q_{pl} = 10^2$ for the super-Earth Kepler-18b. These values are at the high end of those estimated for solar system giants (Goldreich & Soter 1966) but comparable to estimates for exoplanets (Jackson et al. 2008). We tidally evolve our systems for 10 Gyr. We note that observed systems may have had less time to tidally evolve, and a shorter evolution with a proportionally smaller $Q$ will give the same outcome.

4. RESULTS

Our N-body simulations show that in most cases the systems resolve to one of two outcomes on timescales much shorter than the integration duration: either all of the inner planets are destroyed (usually by collision with the star), leaving a single eccentric giant; or the giant is ejected by the inner planets, leaving 1–3 inner planets in the system, all of low mass. Examples of orbital evolution leading to these outcomes are shown in Figure 2.

For our chosen systems, we explore varying the giant planet’s pericenter and semimajor axis (Figure 3). So long as the giant’s orbit is intersecting at least one of the inner planets’, the majority of integrations lead to one of the two outcomes in less than 1 Myr (Figure 4). For tidal circularization of the giant’s orbit to form a true hot Jupiter, the pericenter must be a few hundredths of an AU (see below); within this distance, nearly all of our simulations result in either ejection of the giant or destruction of all the inner planets. The overwhelming outcome is that the three inner planets are destroyed, most commonly by collision with the star, although in some cases the giant accretes one or more, which may significantly enrich the core of the giant. Indeed, many hot Jupiters are observed to have enriched cores (e.g., Guillot et al. 2006). After evolving our surviving giant planets under tidal forces, we find that giants that have accreted one or more inner planets are more likely to become hot Jupiters than those that have not, although the relative infrequency of collision means that most of the hot Jupiters we form have not accreted other planets (Table 3). Due to the extreme collision velocities at these small orbital radii, the giant’s radius may be inflated by colliding with a smaller planet (Ketchum et al. 2011), while the impact velocity when two smaller planets collide can be several times their escape velocity, meaning that collisions may generate copious debris (Leinhardt & Stewart 2012). The inclination of the giant planet with respect to the inner planets does not have a strong effect on the outcome, although with a retrograde giant the fraction of destroyed inner planets colliding with the giant rather than the star rises slightly, as does the number of coexisting systems when the initial $q < 0.10$ AU.

While the ejection of a Jovian planet by Neptune-sized ones may seem surprising, the ratio of ejections of the incoming giant to destruction of the inner planets can be understood in terms of the orbital energies of the two components (Figure 5): as the orbital energy of the giant is decreased (whether through lower mass or through higher semimajor axis), ejection becomes more likely.
fraction of their Hill radius (Johansen et al. 2012; Petrovich et al. 2015b); equivalently, the ratio of their escape velocity to orbital velocity is small, meaning that orbits are not perturbed as much during close encounters. However, for the highly eccentric planets we consider here, ejection is easily achieved because a small transfer of energy from the inner planets to the giant can lead to a significant change in the latter’s semimajor axis. Ejection of the giant is a common outcome for the most massive systems of inner planets we consider when the giant comes in on a wide orbit, but is rare when the inner planets are less massive or the giant’s semimajor axis is smaller.

Giant planets that destroy the inner planets experience some change to their orbital elements (Figure 6). Pericenters may change slightly, while semimajor axes may be significantly reduced. Many of the surviving giants maintain the small pericenters needed for tidal circularization, and will become hot Jupiters after long-term tidal evolution: after 10 Gyr, between 8% and 23% of giants in our integrations circularize to $e < 0.1$. 

Figure 3. Outcomes of our simulations, after 1 Myr of orbital evolution, shown as stacked bars as a function of the giant planet’s initial pericenter $q$. Blue shows systems where the giant destroys the inner planets (possibly by accreting one or more of them), red/orange shows systems where the giant is lost (usually by ejection, although collisions with the star can occur at $q = 0.01$ AU), and the grays show systems where the giant and at least one inner planet coexist after 1 Myr. In a small number of systems, all planets are lost (yellow), or energy conservation is poor (black). Red triangles mark the initial semimajor axes of the inner planets. Yellow and red circles show the systems to scale (planet radii inflated by a factor of 50). When the giant’s pericenter comes inside the semimajor axis of the outermost inner planet, most integrations result in ejection of the giant or destruction of the inner planets. Destruction of the inner planets is favored unless the inner planets are very massive (as in Kepler-18 and -58) and the giant is weakly bound ($a = 10$ AU).
depending on the inner planet configuration and the initial semimajor axis of the giant planet (see Table 3). The final semimajor axes of these hot Jupiters are \( \lesssim 0.06 \) AU, implying pre-circularization pericenter distances (after interaction with the inner planets) of \( \lesssim 0.03 \) AU.

We also form a population of giant planets with large pericenters \( (q \gtrsim 0.05 \) AU, too large for tidal circularization), relatively small semimajor axis \( (a \lesssim 1 \) AU), and moderately high eccentricity \( (e \gtrsim 0.5) \). It is hard to populate this region through in situ scattering of close-in giant planets that may have migrated through a protoplanetary disk (Petrovich et al. 2015b), since planets scattering from these semimajor axes are inefficient at exciting eccentricity from circular orbits as they are in a regime favoring collisions; see the discussion above and Petrovich et al. (2015b).

Either of these pathways entails certain constraints on the perturber exciting the eccentricity, and in particular it is not

Table 3

| System         | Form HJ | Do not form HJ |
|----------------|---------|----------------|
| Kepler-18, \( a = 10 \) AU | 146 (22%) | 509 (78%) |
| Accreted planet | 150 (13%) | 987 (87%) |
| Did not accrete | 204 (36%) | 365 (64%) |
| Kepler-18, \( a = 1.25 \) AU | 407 (11%) | 3174 (89%) |
| Kepler-23, \( a = 10 \) AU | 90 (17%) | 445 (83%) |
| Kepler-58, \( a = 10 \) AU | 322 (12%) | 2344 (88%) |
| Kepler-339, \( a = 10 \) AU | 49 (12%) | 361 (88%) |
| Kepler-339, \( a = 1.25 \) AU | 178 (8%) | 2108 (92%) |
| Kepler-339, \( a = 1.25 \) AU | 138 (26%) | 384 (74%) |
| Kepler-339, \( a = 1.25 \) AU | 434 (22%) | 1559 (78%) |
| Kepler-339, \( a = 10 \) AU | 184 (40%) | 280 (60%) |
| Kepler-339, \( a = 10 \) AU | 507 (14%) | 3114 (86%) |

Note. “Hot Jupiter” is here defined to be a planet that becomes tidally circularized to \( e < 0.1 \).
clear to what extent the conditions needed to trigger secular chaos are met in practice (Davies et al. 2014). Our model of a high-eccentricity giant interacting with inner planets permits us to populate this same region, without relying on suitable parameters of the exciting body. Unfortunately most Kepler candidates do not have measured eccentricities, but we still can...
compare the numbers of giant planets in semimajor axis bins; from our simulations, after 10 Gyr of tidal evolution we find around 2–3 times more giant planets in the range $a \in (0, 0.1)$ AU than in $a \in (0.1, 0.76)$ AU (corresponding to a 240 day period) after correcting for the geometrical transit probability, while in our Kepler sample, we find only around 50% more (Table 4). Hence, our results are consistent with the observed population, as we might expect the “warm Jupiter” region beyond 0.1 AU to be populated to some extent by disk migration (Lin et al. 1996)—which better explains the low-eccentricity warm Jupiters—while some of the hot Jupiters may be destroyed as a result of tides raised on the star (Valsecchi & Rasio 2014). We can also consider the planet population detected by RV surveys. A query of the Exoplanet Orbit Database (http://exoplanets.org/), Han et al. 2014, accessed 2015 May 16) revealed 354 RV-detected planets with masses above 0.3 $M_J$. Of these, 33 lie within 0.1 AU and 59 between 0.1 and 0.76 AU, 13 of the latter having $e > 0.4$. When weighted by their geometric transit probability, this sample has a higher fraction of hot to warm Jupiters than the KOI sample (see Table 4), more in line with the ratio from our simulations. However, if we divide the warm Jupiters into two eccentricity bins at $e = 0.4$ (above which in situ scattering is inefficient at exciting eccentricity (Petrovich et al. 2015b), and below which tidal circularization and/or interaction with the inner planets cannot reach), we find over 8 times as many hot Jupiters as eccentric warm Jupiters. This may point to a contribution from disk migration to the low-eccentricity warm Jupiter and hot Jupiter populations, although a detailed treatment of the differences between the RV and KOI samples is beyond the scope of this paper.

When the incoming giant is ejected, the inner planets often experience some perturbation. Collisions of inner planets with each other or with the star are common, and the interaction with the giant often leaves systems with only one or two of the original three planets. The eccentricities of inner planets can be strongly excited (Figure 6), and single survivors in particular can reach very high eccentricities. However, these eccentricities may not survive in the long term, as tidal circularization acts on the planets’ orbits on long timescales: Figure 6 shows that most eccentricities will decay to zero within 10 Gyr. In contrast, mutual inclinations of the inner planets are not strongly affected, although very flat systems do not retain their coplanarity: initially flat and moderately inclined (by a few degrees) systems show similar inclination distributions after ejection of the giant (Figure 7).

Finally, we discuss the systems where the giant and at least one low-mass inner planet coexist at the end of the integration, shown in gray in Figure 3. In the overwhelming majority of these systems, the giant planet’s pericenter lies beyond the orbit of the outermost inner planet, and the final coexisting system looks much like the initial setup, retaining a highly eccentric giant on a wide orbit with one or more low-mass planets close to the star; the number of inner planets may however be depleted by collisions. Interestingly, we do find a very few cases (23 in number) where at the end of the integration the giant planet’s semimajor axis is smaller than that of the outermost surviving inner planet. In 17 of these cases, all from the Kepler-58 simulations, both the giant and planet d lie beyond 1 AU; in 6 of these, an additional planet remained at ~0.09 AU. In the remaining six cases, three each in the Kepler-58 simulations and the Kepler-18 simulations with the giant starting at 1.25 AU, the giant planet has collided with a b-c merger product, and the specific energy of the resulting body is sufficiently low that its orbit lies interior to that of planet d. Five of these systems survived integration for 10 Myr, and in all cases the giant planet’s pericenter is sufficiently small as to permit tidal circularization and the formation of a hot Jupiter. In these five systems, the mutual inclination is very high, oscillating around 90° and hampering the prospects for detection of both planets by transit photometry. However, these hot Jupiters with surviving companions form only 0.5% of hot detections formed in the Kepler-18, $a = 1.25$ AU integrations and 0.9% of those formed in the Kepler-58 integrations. Hence, while the survival of companion planets is possible given the right conditions (i.e., sufficiently massive inner planets), it occurs in only a tiny fraction of even these systems. We show the semimajor axes and eccentricities of planets in these coexisting systems in Figure 8, highlighting the few systems in which the giant planet lies interior to one of the smaller ones.

5. DISCUSSION

5.1. The Evolutionary Context of Our Simulations

Our method assumes that the evolution of the system can be broken into three stages: an initial stage of excitation of the giant planet’s eccentricity, interaction of the highly eccentric giant with any inner planets, and subsequent tidal circularization of surviving planets’ orbits. We do not explicitly treat the initial phase, since the parameter space of mechanisms and perturbers is very large, and the combination of the small integrator step size needed to resolve the inner planets’ orbits conflicts with the long timescales (which can be over $10^8$ years, Wu & Lithwick 2011) needed to excite the eccentricity of the giant planet. The setup for our simulations is probably most accurate for a scattering scenario, where the giant planet’s pericenter is impulsively changed to a very low value. In a Kozai or other secular scenario with a smoother eccentricity excitation, it is likely that the secular evolution will either continue until the timescale for secular evolution is comparable to the timescale for interaction between the inner planets and

| System          | $a < 0.1$ AU | $0.1$ AU $< a < 0.76$ AU |
|-----------------|-------------|--------------------------|
| Kepler-18       | 10675       | 4732                     |
| Kepler-18, $a = 1.25$ AU | 23108 | 8474                     |
| Kepler-23      | 14740       | 6184                     |
| Kepler-58      | 8292        | 4024                     |
| Kepler-339     | 20273       | 6020                     |
| Kepler-339, $a = 1.25$ AU | 24557 | 7605                     |

| KOIs           | 189         | 125                      |
| RV-detected    | 677         | 255                      |
| RV-detected, $e > 0.4$ | ... | 80                      |

Note. We weight each planet by $1/(a(1 - e^2))$ to correct for the geometric transit probability. Below the line we show the numbers of KOIs with $R > 8R_\oplus$ from the Q1–Q16 KOI list with the $L + 11$ and no FP cuts, as well as a sample of RV-detected giant planets (see the text).
Figure 7. Distributions of mutual inclinations of surviving inner planets in Kepler-18 systems that lost their giant. (A): With a spread of mutual inclinations up to 10°. We also mark the initial distribution (not to scale). (B): Initially coplanar inner planets. In both cases the inner planets are not usually significantly excited, although there is a tail of inclinations above 10°. The distributions arising from the initially coplanar case and the initially inclined case are not significantly different.

Figure 8. Final (neglecting tidal effects) orbital elements of the giant planets (black) and low-mass inner planets (red) in the integrations in which both the giant and at least one of the inner planets are present after 1 Myr. “Inner” planets that now lie exterior to the giant are marked with large red stars, and planets in these systems are linked with black lines.
the giant (see Figure 4), at which point our integrations begin, or that the interaction with the inner planets briefly halts the secular cycle until they are destroyed (similar to the effects of general relativistic precession, Wu & Murray 2003), after which the secular cycle may resume. Note that the destruction of the inner planets can occur at pericenters wider than those at which the giant’s orbit actually overlaps the inner planets’ (Figure 3).

We also neglect any further effect of the body perturbing the giant planet during our integrations and after they have finished. This is again the most accurate for a scattering scenario, where the swift reduction of the giant’s apocenter following interaction with the inner planets would decouple the giant planet from its original perturber. In a secular or Kozai scenario, the secular cycles may resume after the inner system has been cleared, which will affect the statistics of hot and warm Jupiters we have estimated (Tables 3 and 4). Following the entire evolution of these systems from initial eccentricity forcing through to final tidal circularization would be a fruitful avenue of future research.

Although we have not treated the full evolution of these systems in this work, we can attempt to relate the outcomes of the integrations to the eccentricity excitation mechanism. In particular, a large semimajor axis of the giant planet increases the probability that it will be ejected instead of destroying the inner system. Driving a planet’s pericenter to very small distances by scattering from very wide orbits (note that to achieve a semimajor axis of 10 AU, the scattering event would have to take place at around 20 AU) is difficult (Mustill et al. 2014), and the giant planets that we find vulnerable to ejection when they interact with the inner planets may be more likely to have been excited by Kozai perturbations from a wide binary companion.

5.2. Robustness of Our Findings

The main result of our study—that giant planets with sufficient orbital eccentricity to become hot Jupiters destroy low-mass inner planets in the system—is robust to the masses of these inner planets so long as they are not so massive as to eject the giant. In the absence of damping mechanisms that can separate and circularize orbits, the intersecting orbits of the giant and the inner planets lead to either collisions or ejections until orbits no longer intersect. In contrast, in very young systems, eccentricity can readily be damp by the protoplanetary gas disk or by massive populations of planetesimals, helping to explain why Type II migration of giant planets does not totally suppress the formation of other planets in the inner parts of these systems: bodies thrown out by the giant can recircularize and accrete outside its orbit (Mandell et al. 2007).

In our systems, in contrast to systems during the protoplanetary disk phase, gas is no longer present, and massive planetesimal populations are impossible to sustain close to the star for long timescales (Wyatt et al. 2007). Two additional sources of damping may play a role in these systems. First, debris may be generated in hypervelocity collisions between inner rocky planets, but integrations with the mass of the Kepler-339 planets distributed among 100 smaller bodies did not show significant damping of the giant’s eccentricity. Second, tidal circularization acts, but on timescales much longer than the time for planet–planet interactions to end in our systems.

6. CONCLUSIONS

We have shown that high-eccentricity migration of a giant planet to form a hot Jupiter necessarily leads to the removal of any preexisting planets on orbits of a few tenths of an AU in the system, thus accounting for the observed lack of close companions to hot Jupiters. This supports a high-eccentricity migration scenario for hot Jupiters, as migration through a protoplanetary gas disk usually does not fully suppress planet formation (Fogg & Nelson 2007a, 2007b; Mandell et al. 2007; Ketchum et al. 2011; Ogihara et al. 2014). We find that under high-eccentricity migration, when the giant’s pericenter is sufficiently small to permit tidal circularization, either the giant or the inner planets must be lost from the system. A very small fraction (<1% even with favorable parameters) of the hot Jupiters we form do end up interior to a surviving low-mass planet, but this outcome is very uncommon: if such a low-mass close companion to a hot Jupiter were to be found in the future, it would mean that in that system at least the migration almost certainly proceeded through a disk. When the giant planet does destroy the inner system, the interaction sometimes raises the pericenter of the eccentric giant planets sufficiently to prevent tidal circularization, providing a novel way of producing eccentric warm Jupiters; other giants whose pericenters are initially too high for tidal circularization may be brought to populate the same region as they lose energy due to interaction with the inner planets.

It is unknown which mechanism of eccentricity excitation dominates, be it scattering, the Kozai effect, or low-inclination secular interactions, but we expect that the inability of inner planets to survive in systems forming hot Jupiters will remain a robust result when future simulations coupling the evolution of the outer system, driving the giant’s eccentricity excitation, and the inner system are performed.

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