The origins of nearly coplanar, non-resonant systems of close-in super-Earths

Leandro Esteves,1⋆ André Izidoro,1,2† Sean N. Raymond,3 Bertram Bitsch4

1UNESP, Universidade Estadual Paulista, Grupo de Dinâmica Orbital e Planetologia, Guaratinguetá, CEP 19516-410, SP, Brazil
2Department of Earth, Environmental and Planetary Sciences, MS 126, Rice University, Houston, TX 77005, USA
3Laboratoire d’astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, 33615 Pessac, France
4Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

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ABSTRACT
Some systems of close-in “super-Earths” contain five or more planets on non-resonant but compact and nearly coplanar orbits. The Kepler-11 system is an iconic representative of this class of system. It is challenging to explain their origins given that planet-disk interactions are thought to be essential to maintain such a high degree of coplanarity, yet these same interactions invariably cause planets to migrate into chains of mean motion resonances. Here we mine a large dataset of dynamical simulations of super-Earth formation by migration. These simulations match the observed period ratio distribution as long as the vast majority of planet pairs in resonance become dynamically unstable. When instabilities take place resonances are broken during a late phase of giant impacts, and typical surviving systems have planet pairs with significant mutual orbital inclinations. However, a subset of our unstable simulations match the Kepler-11 system in terms of coplanarity, compactness, planet-multiplicity and non-resonant state. This subset have dynamical instability phases typically much shorter than ordinary systems. Unstable systems may keep a high degree of coplanarity post-instability if planets collide at very low orbital inclinations (≲1°) or if collisions promote efficient damping of orbital inclinations. If planetary scattering during the instability takes place at low orbital inclinations (i≲1°), orbital inclinations are barely increased by encounters before planets collide. When planetary scattering pumps orbital inclinations to higher values (≳1°) planets tend to collide at higher mutual orbital inclinations, but depending on the geometry of collisions mergers’ orbital inclinations may be efficiently damped. Each of these formation pathways can produce analogues to the Kepler-11 system.

Key words: planetary systems: protoplanetary disks — planetary systems: formation

1 INTRODUCTION
At least 30% of main sequence stars host planets with sizes between 1 and 4 Earth radii or masses less than 20 M⊕ on orbital periods shorter than 100 days (Mayor et al. 2011; Howard et al. 2012; Winn & Fabrycky 2015). This population contains both high- and low-density planets (Rogers 2015; Wolfgang et al. 2016). Given that our focus is solely on their formation, we refer to this entire category of planets as hot super-Earths.

Two key constraints on formation models are the observed multiplicity and period ratio distributions of super-Earths. Among transiting super-Earth systems only ~20% are found in multiple planets systems (N>2). The remaining ~80% contain only a single transiting planet (Fang & Margot 2012; Tremaine & Dong 2012; Johansen et al. 2012). This has been called the Kepler dichotomy, and it is not clearly found in radial velocity systems (e.g. Figueira et al. 2012). Adjacent super-Earths in multi-planet systems are rarely found in mean motion resonances (Fabrycky et al. 2014). Notable exceptions include the Kepler-223 (Mills et al. 2016) and TRAPPIST-1 (Gillon et al. 2017; Luger et al. 2017) systems.

The migration model proposes that super-Earths formed at larger distances from their stars and migrated inwards by interactions with gaseous protoplanetary disks (Terquem & Papaloizou 2007; McNeil & Nelson 2010; Ida...
& Lin 2010). In this model super-Earths pile up near the
disk’s inner edge, forming long chains of planets locked in
first order mean motion resonances. After the gas disk dissi-
pates (or just before), most resonant chains becomes dynam-
ically unstable (Izidoro et al. 2017, 2019). We call systems
“unstable” if they undergo a phase of instability near the
end of the gas disk lifetime and refer to the phase of sub-
sequent collisions as the “late instability phase”. Instability
triggers scattering events among planets, breaks resonances
and leads to giant impacts. Close to the star collisions are
favoured with respect to ejections because of high escape ve-
locities from the star and short orbital periods (e.g. Safronov
1972; Benz 1983; Thommes & Jacobson 2014; Izidoro et al. 2017, 2019; Raymond
et al. 2018b; Lambrechts et al. 2019; Izidoro et al. 2019).

Surviving systems have orbits that are more spread out and
dynamically excited than in the resonant chain phase. Sys-
tems that do not go dynamically unstable and stay in long
resonant chains during the entire course of the simulations
from Izidoro et al. (2019) are refereed as “stable” systems.

These simulations do no take into account other potential
mechanisms that may help to trigger dynamical instabilities –
in systems that remained stable during the entire course of
their simulations – as for instance the effects of tidal dissi-
pation, general relativity, planetesimal scattering and mag-
netosperhic rebound (e.g. Bolmont et al. 2014; Goldreich
& Schlichting 2014; Chatterjee & Ford 2015; Liu et al. 2017).
We here assume that the instability phase is the source of
the observed period ratio distribution of super-Earth systems.

Simulations show that the migration model matches the
period ratio distribution of Kepler super-Earths if 90-99% of
resonant chains become unstable (Izidoro et al. 2017, 2019).
The same sample of systems matches the Kepler dichotomy
because the considerable mutual inclinations between plane-
tary orbits decreases the probability of finding many planets
transiting in the same system (see also Mulders et al. 2018).

This argues that most single-transit systems are inherently
multiple planet systems, in agreement with radial velocity
surveys (e.g. Figueira et al. 2012).

At first glance the migration model predicts that all
stable systems should end up with many planets on copla-
nar, resonant orbits. When the viewing geometry is aligned
with the planets’ orbital plane, many planets should be de-
tected in transit. In contrast, unstable systems should pro-
duce planets on non-coplanar, non-resonant orbits. Rarely
should many planets be found to transit in the same system
in this case.

There exists an observed category of system that is hard
to understand in the framework of the migration model that
contains many transiting planets on near-coplanar but non-
resonant orbits. The Kepler-11 (Lissauer et al. 2011) and
Kepler-20 (Fressin et al. 2012; Gautier et al. 2012) systems
are representative members of this class (see Fig. 1). Six
planets are known to transit in Kepler-11 with orbital pe-
riods between 10 and 118 days (semi-major axis between
0.091 au and 0.466 au) and mutual orbital inclinations of
at most 1 or 2 degrees (Lissauer et al. 2013). The Kepler-
20 system hosts two Earth-sized planets and four larger
super-Earths, all with orbital periods between 3.69 and 77.61
days (semi-major axis between 0.045 au and ~ 0.345 au).

Five of the six planets transit their star, but the second-
outermost planet was discovered with the radial velocity
technique (Buchhave et al. 2016). Kepler-11’s and Kepler-
20’s stellar ages have been estimated at 3.2±0.9 Gyr (Bedell
et al. 2017) and 7.6±3.7 Gyr (Buchhave et al. 2016), respec-
tively, indicating that each system is long-term stable (see
also Migaszewski et al. 2012; Mahajan & Wu 2014; Hands
et al. 2014; Mia & Kushvah 2016; Jontof-Hutter et al. 2017).

Our paper is laid out as follows. In §2 we present the
setup of our simulations. Next we describe how we mined the
outcome of these simulations to find 12 Kepler-11 analogue
systems (§3). In §4 we show the typical formation pathway
of these systems. We discuss our results and their implications
in §5.

2 SIMULATIONS

We simulated the growth and dynamical evolution of sys-
tems of super-Earths during and after the gaseous disk
phase (following from Izidoro et al. 2019). Our code is based
on the N-body code Mercury (Chambers 1999), to which
we have added synthetic forces designed to mimic essential
planet formation processes. These include a prescription for
disk evolution and dispersal (following Bitsch et al. 2015),
growth of planetary embryos by pebble accretion (Johansen
& Lambrechts 2017), adopting a simple model for how the
pebble flux evolves in time (Izidoro et al. 2019), tidal interac-
tions between growing planets and the gas disk that lead to
eccentricity and inclination damping (Tanaka & Ward 2004;
Cresswell & Nelson 2008) as well as orbital migration (Ward
1997; Paardekooper et al. 2011). Collisions between growing
bodies occur naturally and are treated as inelastic mergers,
conserve mass and linear momentum.

Our analysis is based on a subset of simulations from
Izidoro et al. (2019), specifically their Model-I, II, and III
runs. Our simulations start from a distribution of planetary
seeds with masses of 0.005 to 0.015 Earth masses extend-
ing from either 0.7 to 20 AU (model I, a and b analogue
indexes), 0.7 to 60 AU (model II, c), or 0.2 to 2 AU (model
III, d). Simulations of Model-I from Izidoro et al. (2019)
with nominal pebble flux and disk age (model I, b) did not
produce Kepler-11 analogues (see discussion below).

Seeds were given small but non-zero starting inclina-
tions and eccentricities. Our simulations involve a flux of peb-
bles spiralling inward through the disk due to aerodynamic
drag (see, e.g., Lambrechts & Johansen 2014). The inner
dge of the gaseous disk was set at 0.1 AU, consistent with
analyses of the Kepler super-Earths (Mulders et al. 2018)
and as also found from radiation hydrodynamical simula-
tions of the inner disc edge (Flock et al. 2019). The different
models make different assumptions about the pebble size in
the inner rocky parts of the disk as well as the disk mass
at the start of the simulation, calibrated to match a given
time in the evolution of our canonical disk model (taken
from Bitsch et al. 2015). In our simulations, seeds grow by
accreting pebbles and eventually become massive enough to
migrate (all the while continuing to accrete pebbles).

Convergent migration leads to collisions among growing seeds,
which feeds back on the migration rate. Growing planets
may eventually reach pebble isolation mass (Bitsch et al.
2018), where the pebble isolation mass in the inner disc
regions could explain the presumed masses of the Kepler
planets (e.g. Wu 2019; Bitsch 2019). After the dissipation
of the gaseous disk, each simulation was integrated for an-
other 50 Myr taking only gravitational perturbations into account. Simulations from Izidoro et al. (2019) do not take into account gas accretion onto planetary embryos. For full technical details of the code and setup, see Izidoro et al. (2019), Bitsch et al. (2019), and Lambrechts et al. (2019).

In our analysis we made use of the subset of simulations from Izidoro et al. (2019) that formed super-Earth systems roughly consistent with observations in terms of their masses (see Wolfgang et al. 2016) and period ratio distributions (see Fabrycky et al. 2014). This amounts to a total of 221 simulations.

3 MINING OUR SIMULATIONS FOR KEPLER-11 AND KEPLER-20 ANALOGUES

Figure 1 shows the orbital architecture of twelve Kepler-11-like systems selected from our simulations.

We used four criteria to select Kepler-11 analogues, applied to planets within 0.7 AU:

(i) Systems could not contain more than one planet pair in first order mean motion resonance. The so called stable systems do not match this first constraint so all our selected systems come from unstable systems of Izidoro et al. (2019).

(ii) Systems must have mean period ratios between adjacent planets within ±15% of the Kepler-11 value of 1.68.

(iii) Mutual inclinations between planetary orbits must be small enough that five or more planets could be observed in transit.

(iv) Systems must maintain dynamical stability and criteria 1-3 over at least 1 billion years when we extend our simulations from 50 Myr to 1 Gyr.

We will discuss how the fraction of Kepler-11 like systems in our simulations compare to observations in Section 5.

A nice example simulation – analog_c5 – contains 6 planets between 0.07 AU and 0.42 AU. Only the outermost pair of super-Earths appears to be in 2:1 resonance (in fact one of the resonant angles associated with the 2:1 mean motion resonance librates and circulates). The mean period ratio between planets in this system is 1.688, very close to the Kepler-11 value of 1.68 (The mean period ratio of the Kepler-20 planet pairs is ~1.84). Considering the estimated masses of the Kepler-11 and Kepler-20 planets (Lissauer et al. 2011; Bedell et al. 2017; Buchhave et al. 2016; Wolfgang et al. 2016) we have also calculated the mean mutual Hill radii of these systems. To calculate the mean Hill radius of each system we first calculated the mutual Hill radii of adjacent-planet pairs in the system and then we average over the pairs in the system.

Using the upper and lower limits of their estimated masses, the mean mutual hill radii of the Kepler-11 system are 12.85 and 14.45, respectively. For the Kepler-20 system, these metrics ranges between 14.35 and 16.10. The mean separation in mutual Hill radii of our twelve selected systems are between 13 and 16.5. The mean mutual Hill radii of analog_c5 is 14.76. This shows that the compactness of our selected systems compares well with those of Kepler-11 and Kepler-20 systems not only in terms of orbital period ratio of adjacent planet pairs but also in terms of their mutual Hill radius. Thus, both Kepler-11 and Kepler-20 systems are consistent as being the outcome of dynamical instabilities rather than being necessarily the outcome of type-I migration in inviscid disks that may produce compact systems that fail to form resonant chains (McNally et al. 2019).

To estimate the probability of finding multiple planet systems, we simulated the geometric transit probability from a range of observing angles. Figure 2 shows how the detectability of five simulated systems varies as a function of the azimuthal angle $\phi_{\text{obs}}$ of an observer along a reference plane and the inclination of the observer $i_{\text{obs}}$ with respect to that same plane. Each axis was divided into 200 points and at each point and for each planet in a given system, we calculated the height of the planet relative to the system.
tem reference plane $z_{\text{plane}}$ and the height of the observer $z_{\text{obs}}$ relative to same plane. We imposed a minimum impact parameter of 0.9 (such that $z_{\text{det}} \leq 0.9r_{\text{star}}$) to indicate a transit detection for a given planet.

The color scale in Fig. 2 illustrates the number of planets detected in transit at each line of sight. For a almost perfectly coplanar system the region the number of planets seen in transit changes in time as the planets exchange mutual inclinations and the full 5-6 planet systems are seen in transit throughout. This may be analogous to Kepler-11 (see Fig. 2). However, in two other cases (a4 and c3) the number of planets seen in transit changes in time as the planets exchange orbital angular momentum, inducing fluctuations in mutual inclinations. This may be representative of the Kepler-20 system, in which only 5 of 6 known planets transit.

Fig. 2 shows that in many simulated systems five or more planets could be detected in transit. Of course, this only represents a snapshot in time. To understand the long-term evolution of these systems, and to ensure that their transit detection is maintained, we integrated these systems for 1 Gyr past their final configuration at 50 Myr obtained from Izidoro et al. (2019). We only included planets within 0.7 AU to reduce the computing time need.

The systems in Fig. 1 are those that maintained dynamical stability during their long-term integrations. We have extended the simulations of Izidoro et al. (2019) using the hybrid integration algorithm of Mercury package (Chambers 1999). We use an integration timestep smaller than 1/20 of the orbital period of innermost planet in the system. Any additional instability phase would reduce the system planet multiplicity, spread out the planets’ orbits, and increase mutual inclinations, likely making it impossible to detect many planets in transit. Five of our initial candidates in fact became unstable in our long-term integrations and were discarded, and they are not shown in Figure 1. Fig. 3 shows the evolution of the planets’ inclinations in four systems that remained stable for 1 Gyr. The color scale represents the number of planets seen in transit for an observer at $\phi_{\text{obs}} = 0$ and $i_{\text{obs}} = 0$ over the systems evolution. Two systems (analogs a1 and c5) maintained extremely low mutual inclinations and the full 5-6 planet systems are seen in transit throughout. This may be analogous to Kepler-11 (see Fig. 2). However, in two other cases (a4 and c3) the number of planets seen in transit changes in time as the planets exchange orbital angular momentum, inducing fluctuations in mutual inclinations. This may be representative of the Kepler-20 system, in which only 5 of 6 known planets transit.

4 FORMATION PATHWAYS OF KEPLER-11 ANALOGUE SYSTEMS

We now investigate the formation of the Kepler-11 analogue systems selected in the previous section. The top panel of Figure 4 shows the mean orbital inclination of planets just before they collide (when they touch) during the instability phase and the final mergers’ orbital inclinations. Each point/star represents the mean value calculated over all planets colliding in a given system during the instability phase. Kepler-11 like systems come in two flavours. They have either very low orbital inclinations when they collide or exhibit very efficient damping of orbital inclination by collisions. Kepler-11 like systems have final planets with mean orbital inclinations typically lower than ~1 degree. It is possible to understand these results from the lower panel of the same figure.
While the top panel of Figure 4 show systems’ mean values, its lower panel shows the orbital inclination of individual planets (in fact this is the largest inclination of any two colliding bodies) just before they collide during the instability phase. The vertical axis shows merger inclinations just after the collisions. Again, stars show Kepler-11 like systems, but now small-dots show systems with at least 5 planets that do not qualify as Kepler-11 like systems following our criteria. The color shows the difference of the longitude of the ascending nodes of colliding planet pairs just before the collision.

When planetary scattering during the instability phase takes place very close to the system’s invariant plane ($i < h_{\text{rmh}} = \frac{R_{\text{hill}}}{a} = \frac{\sqrt{m_j m_k}}{m_j + m_k} \lesssim 1^{\circ}$; $h_{\text{rmh}}$ is the reduced mutual Hill radius) the orbital inclination increases very slowly by encounters (Ida 1990) and planets created by mergers tend to have very low inclination orbits, independent on the bodies orbital alignment during the collision (Matsumoto & Kokubo 2017, see orange data points in the lower panel of Figure 4). If the orbital inclination of colliding bodies is sufficiently low ($i \lesssim \frac{v_c}{v_k} = 0.5v_{\text{esc}}/v_k$; where $v_{\text{esc}}$ and $v_k$ are the escape (combining the masses of $i$ and $j$) and Kepler velocity, respectively) the $|v_z|$ velocity component is small and $v_z$ is accelerated due to the gravitational focusing during the approach (Matsumoto & Kokubo 2017). If the velocity change is larger than $|v_z|$ then the longitude of the ascending nodes of the approaching bodies change such as $\Omega_i - \Omega_j = 180^{\circ}$ and inclination gained during the encounter is mostly damped by the collision (Matsumoto & Kokubo 2017, see black data points in the lower panel of 4). If bodies eventually reach $i \gtrsim \frac{v_c}{v_k} = 0.5v_{\text{esc}}/v_k$ during planetary scattering, gravitational focusing may not have time to align the nodes before the impact (Matsumoto & Kokubo 2017). In this case, the damping of orbital inclination may not be very efficient (e.g. red and green dots in the lower panel of Figure 4). Damping of orbital inclination occurs in most collisions (Figure 4) in agreement with Matsumoto & Kokubo (2017). Collisonal damping of orbital inclination may occur at any distance from the star. However, because collisions are more likely to occur close to the star due to shorter dynamical timescales and higher escape velocities this inclination damping mechanism is probably far more efficient in close-in regions than further out.

Figure 5 shows the growth of the planets in our best Kepler-11 analogue, the analog $c5$ system. Shortly before the final dissipation of the gas disk a dynamical instability was triggered (see for instance Goldreich & Schlichting (2014) and Pichierri et al. (2018); Pichierri & Morbidelli (2020) for a detailed discussion on the onset of dynamical instabilities in resonant chains). While it led to a number of collisions, merger planets had very low (mutual) orbital inclinations because planetary scattering during the instability phase took place near the system invariant plane (in this case is also near the disk midplane) such that orbital inclinations grew very slowly (Ida 1990). As collisions conserve linear momentum, the merger planets also have very low mutual orbital inclinations. The instability phase in this system was quite short and ended before the gas fully dissipated. After the instability phase, there was insufficient time for planets to restore a resonant configuration before the gas fully vanished. In fact planets did not migrate significantly post-instability in this simulation. Although it is difficult to infer the exact role of the gas tidal effects for the final outcome of the dynamical instability (but see also Kominami & Ida (2002) and Iwasaki et al. (2002)) the presence of the gas-disk during the stability phase is not always a required condition to produce our Kepler-11 like systems. This is the
case for example for analog$_{a1}$. In this system, the instability phase started after the gas dispersal yet the planets remained on extremely low-inclination orbits ($\sim 0.1\degree$). This inclination range is comparable to that of planets in analog$_{c5}$ (Figure 5). For the analog$_{a1}$, the key ingredient to produce a almost coplanar system is the fact that planet collided at super-low mutual orbital inclinations (Matsumoto & Kokubo 2017). For systems like analog$_{a1}$, the eventual anti-alignment of the longitude of the ascending nodes at collisions is a mere bonus that help to damp already low orbital inclinations even further. About half of our Kepler-11 analogues underwent instabilities after the gas disk was fully gone.

The shortest instability phases of our simulated Kepler-11 like systems were for planets that collided at low orbital inclination (e.g. analog$_{a1}$, analog$_{c5}$, and analog$_{a2}$). We define the duration of the instability phase as the $\Delta t$ between the timing of the first and last collision in the system. We only take into account collisions occurring later than 100 kyr before gas disk dispersal and inside 0.7 au. We expect the instability duration to depend on how fast resonances between planet pairs are broken, the orbital inclinations/eccentricities of planet pairs when this happens, and the number of planet pairs (see Pichierri et al. 2018). Unstable pairs on almost coplanar orbits collide almost immediately while inclined ones typically take longer. As the number of planets and consequently potential collisions in different unstable resonant chains may vary, we normalize the duration of the instability phase of each system ($\Delta t$) by the respective number of collisions during the instability phase ($N_{\text{col}}$). The quantity $\Delta t/N_{\text{col}}$ measures the averaged time between successive collisions during the instability phase, and it is a good proxy to measure how fast collisions take place in different resonant chains. We find that in our Kepler-11 like systems the timing between successive collision is almost always shorter than 0.1 Myr (about 80% of successive collisions). For a $2\sigma$ confidence level $\Delta t/N_{\text{col}}$ yields $(0.278 \pm 0.433)$ Myr in Kepler-11 analogues. For non Kepler-11 analogues (with $N > 4$) it yields: $(2.39 \pm 1.51)$ Myr. In Kepler-11 like systems, collisions happen fast and presumably before inclinations are significantly excited by encounters.

We also did look for other correlations that could exist between the timing of the instability phase and the dynamical state of the systems but we did not find any obvious one. This is true for instance when we measure the onset of the dynamical instability relative to the end of the gas disk dispersal (we did check this correlation for other convenient epochs). The timing of onset of the dynamical instability probably depends on the complex resonant dynamics of each resonant chain. On the other hand, the duration of the impact phase – measured via $\Delta t/N_{\text{col}}$ – may provide insights on the dynamical state of the system when resonances are broken.

In our simulations collisions are considered to be perfectly inelastic and conserve mass and linear momentum. To validate this assumption we have confronted the impact data of our simulations with merging criteria for giant impacts. We find that most giant impacts during the instability phase in our simulations qualify as merging events (e.g. Genda et al. 2012; Kokubo & Genda 2010; Leinhardt & Stewart 2012; Stewart & Leinhardt 2012). Figure 6 shows the normalized impact velocities of collisions during the late instability phase with colors corresponding to merging (black) and hit-and-run (red) collisions. Only 10% of collisions in our Kepler-11 systems fall in the hit-and-run regime; the other 90% are merging. Thus, on average, less than one collision in Kepler-11 systems is a hit-and-run. Among our full sample of simulations the fraction of hit-and-run collisions is about 31%. Our simplistic treatment of giant impacts is also supported by the results of Poon et al. (2019), who found virtually no difference between planetary systems where collisions are considered perfect merging events and where fragmentation is taken into account (see also Wallace et al. 2017). The effects of fragmentation also have minor effects on the formation of terrestrial planets in our solar system (Chambers 2013; Clement et al. 2019).

Finally, in Kepler-11 analogues systems the planets had also lower orbital eccentricities immediately before collisions when compared with most typical simulations, this can be seen clearly in Figure 7. For a $2\sigma$ confidence level the mean orbital eccentricity of planet-pairs just before collisions is $(0.176 \pm 0.0176)$ for Kepler-11 like systems, while for non Kepler-11 like systems it is $(0.253 \pm 0.00762)$. This also supports our claim that as in Kepler-11 like systems collisions typically happen very rapidly there is virtually no time for planets to dynamically over excite each other’s orbit by mutual scattering and encounters. Figure 7 also shows that collisions can efficiently damp orbital eccentricities which in agreement with previous studies (e.g. Raymond et al. 2006; Matsumoto et al. 2015).

5 DISCUSSION

We have shown that Kepler-11-like systems, with highly coplanar but non-resonant orbits, are a natural outcome of the migration model. Of course, they only represent a small sub-population of hot super-Earths. Yet their formation pathway – characterized by collisions at low orbital inclinations or collisions that efficiently damp orbital inclinations due to the anti-alignment of the longitude of the ascending node of colliding bodies – falls within the range of plausible outcomes of our simulations. Such systems are therefore not extreme rarities but simply modestly-rare outcomes of a more general formation scenario characterized by migration of planets into resonant chains, followed by late instabilities (the so-called breaking the chains model; Izidoro et al. 2017, 2019).

One may wonder whether long-range migration is an essential ingredient in producing Kepler-11 analogue systems. We do not think that this is the case. Many different models have been proposed to explain the population of close-in super-Earths (see Raymond et al. 2008, for a comparison between models). A common theme in all models is that super-Earths must form quickly, likely reaching near their final masses during the gaseous disk phase. This implies that the late stages of the gaseous disk phase are likely characterized by the migration of super-Earths, regardless of where and how they actually accreted (Raymond et al. 2018a). The breaking the chains model proposes that, like the awkward teenage years, resonant chains are a phase through which
all super-Earth systems pass, although migration need not always imply resonant chains (McNally et al. 2019). Yet the formation of Kepler-11 analogues relies on the geometry of impacts during the instability phase.

The fraction of Kepler-11 like systems varies between different sets of simulations from Izidoro et al. (2019). Their Model I – with their nominal pebble fluxes and disk ages – produced planets that were typically more than 10 Earth masses. Systems with such massive planets are typically more excited and dynamically spread and none of these systems qualified as a Kepler-11 like system considering our criteria. Kepler-11 like configurations should be more common in lower-mass systems. Izidoro et al. (2019)’s Model-II produced five Kepler-11 like systems, with an occurrence rate of about 10% of the simulations of this model. To compare our results with observations, we conducted simulated observations of our planetary systems and we find that Model-II systems produced 6.4 times more systems with 3 or more observed planets than systems with 5 or more planets. For the Kepler data, this same ratio is much higher, about 17. So, it is quite possible that some of our model overestimates the fraction of high multiplicity systems. However, it is important to keep in mind that high planet multiplicity systems come in two flavours in the context of the breaking the chain scenario: from stable resonant chains such as Kepler-223 or from unstable Kepler-11 like systems. Matching the Kepler data may also require a combination of different disk models (Izidoro et al. 2019). Thus, we caution when comparing the fraction of Kepler-11 like systems produced in our simulations and those in the Kepler data.

Our simulations are admittedly simplified and we do not claim them to be the final answer in planet formation. Nonetheless, they include a diversity of relevant physical effects thought to represent many of the key processes in planet formation. It is also reassuring that the systems we produce bear a strong resemblance to observed systems (see Izidoro et al. 2019, for a discussion).

We did not obtain systems identical to Kepler-11 and Kepler-20. Systems with very compact orbits, such as the first pair of the Kepler-11 system, almost always became unstable in our simulations. However, we note that migration can produce pairs of planets on very close orbits (Raymond et al. 2018b), which may in principle be gently separated on Gyr timescales through tidal friction (Lithwick & Wu 2012; Batygin & Morbidelli 2013; Bolmont et al. 2014).

Looking to the future, it would be interesting to take the compositions and atmospheric envelopes of super-Earths into account together with a more sophisticated model for giant impacts, to see whether there is a correlation with coplanar non-resonant systems. It may also be important to include fragmentation in giant impact models as debris produced in the dynamical instabilities can break resonant chains if the set of debris is massive enough (Chatterjee & Ford 2015). Many planets in the Kepler-11 and Kepler-20
Figure 6. Normalized impact velocities for giant impacts from our simulations as a function of the impact angle. Only collisions occurring during the instability phase are shown. In addition, only are shown collisions where the bodies involved have masses larger than 0.6 Earth mass. Collisions in Kepler-11 like systems are shown as stars and non-selected systems are shown as circles. In both cases, the black (circles or stars) show collisions that qualify as merging events and the red (circles or stars) show collisions that would qualify as hit-and-run collisions. The outcome of our collisions are classified following the criteria by Kokubo & Genda (2010) and Genda et al. (2012).

Figure 7. Mean orbital eccentricity of planets just before collisions in the instability phase and the final mergers’ mean orbital eccentricities. Each data point shows one planetary system. The mean orbital eccentricity just before collision of each system is calculated averaging over all colliding planet pairs of the system but taking the maximum eccentricity of each planet-pair. Kepler-11 like systems are shown as red stars. Non-Kepler-11 like systems appear as dots where dot-colors represent the number of planets in the system inside 0.7AU.

systems have low densities (Lissauer et al. 2013) although Kepler-20b may have a terrestrial composition (Pressin et al. 2012; Gautier et al. 2012).

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APPENDIX A: SECULAR RESONANCES IN OUR SYSTEMS

In order to further understand the dynamics of our planetary systems, we have also mined our data looking for main secular resonances in our final planetary systems. From simulated planet-pairs in Figure 1, 7 planet-pairs exhibit significant (and in most cases multiple) episodes of libration of the resonance angle associated with the main inclination-type secular resonance, while the resonant angles associated with the main eccentricity-type secular resonance mostly circulated (Figure A1). Additionally, we found another 5 planet-pairs where the resonant angle associated with the main eccentricity-type resonance showed significant (and in most cases multiple) episodes of libration, while the resonant angles associated with the main inclination-type secular resonance mostly circulated (e.g. Figure A2, left panel). Only 1 of our planet-pairs show episodes of libration of both angles associated with the eccentricity and inclination types main secular resonances. We consider significant episodes of libration those that last at least 1-10Myr.

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