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Migration-driven diversity of super-Earth compositions

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ABSTRACT

A leading model for the origin of super-Earths proposes that planetary embryos migrate inward and pile up on close-in orbits. As large embryos are thought to preferentially form beyond the snowline, this naively predicts that most super-Earths should be very water-rich. Here we show that the shortest period planets formed in the migration model are often purely rocky. The inward migration of icy embryos through the terrestrial zone accelerates the growth of rocky planets via resonant shepherding. We illustrate this process with a simulation that provided a match to the Kepler-36 system of two planets on close orbits with very different densities. In the simulation, two super-Earths formed in a Kepler-36-like configuration; the inner planet was pure rock while the outer one was ice-rich. We conclude from a suite of simulations that the feeding zones of close-in super-Earths are likely to be broad and disconnected from their final orbital radii.

Key words: protoplanetary discs – planets and satellites: formation – planets and satellites: dynamical evolution and stability – planet-disc interactions – planets and satellites: composition.

1 INTRODUCTION

While the demographics of close-in low-mass planets (broadly referred to as 'super-Earths') have been known for some time (Lissauer et al. 2011; Batalha et al. 2013; Fabrycky et al. 2014), a handful of recent studies have focused on the closest-in planets. The atmospheres of low-mass, extremely hot planets should be entirely photoevaporated away (e.g. Lammer et al. 2003; Baraffe et al. 2006; Hubbard et al. 2007; Raymond, Barnes & Mandell 2008). Within the 'photoevaporation valley' a planet's size must correspond to the solid (atmosphere-free) planet itself (Lopez & Fortney 2013; Owen & Wu 2013; Sanchis-Ojeda et al. 2014; Carrera et al. 2018). From their inferred sizes and masses, the closest-in planets appear to be rocky, not icy (Lopez 2017; Owen & Wu 2017; Van Eylen et al. 2017; Jin & Mordasini 2018).

The formation mode of super-Earths can in principle be inferred from a combination of the planetary system architecture and the planets' bulk compositions, as long as a rough rocky versus icy discrimination can be made (Raymond et al. 2008). To date, seven models have been proposed to explain these planets' origins (see Raymond et al. 2008, 2014). Two viable candidates remain: the so-called *drift* and *migration* models.

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The drift model (Boley & Ford 2013; Chatterjee & Tan 2014, 2015) proposes that a large flux of pebbles drift inwards and pile up at pressure bumps, greatly enhancing the abundance of solids in the inner disc. Most planetary growth takes place close-in and the planets are expected to be rocky. This contrasts with the strict *in-situ* accretion model, which invokes growth close-in without any enhancement of solids relative to gas or orbital migration. The *in-situ* accretion model is not self-consistent because planet growth is so fast that migration is unavoidable (Bolmont et al. 2014; Inamdar & Schlichting 2015; Ogihara, Morbidelli & Guillot 2015).

The migration model (Terquem & Papaloizou 2007; Ogihara & Ida 2009; Ida & Lin 2010; McNeil & Nelson 2010; Cossou et al. 2014; Izidoro et al. 2017) proposes that Earth-mass or larger planetary embryos grow across the disc, migrate inwards, and pile up close to the star. The migration phase produces a chain of resonant orbits in which the innermost planet is anchored at the inner edge of the disc, where a strong positive torque balances the other planets' negative disc torques (Masset et al. 2006; Romanova & Lovelace 2006). When the gaseous disc dissipates, most resonant chains become unstable and the resulting systems have been shown to match the Kepler period ratio and multiplicity distributions (Izidoro et al. 2017). It is generally thought that the planets formed in the migration model should be water-rich. Planetary embryos are expected to grow faster and larger beyond the snowline (Kokubo & Ida 2002;

Morbidelli et al. 2015), and it stands to reason that ice-rich embryos should be the first to migrate.

There is a complication to the simple idea that the migration model produces ice-rich super-Earths. Icy embryos migrate through a zone of presumably rocky bodies (Izidoro, Morbidelli & Raymond 2014). While these rocky bodies are much less massive, the migrating icy embryo may pile up rocky material in inner resonances and in principle accelerate the growth process of rocky planets (Fogg & Nelson 2005; Raymond, Mandell & Sigurdsson 2006; Mandell, Raymond & Sigurdsson 2007; Izidoro, Morbidelli & Raymond 2014). Thus, even if the migrating bodies are icy, the planets closest to the star may be purely rocky, and some rocky embryos may grow fast enough to migrate. In addition, any embryos – including those that originate past the snowline – are subject to water loss from ²⁶Al heating if they form quickly (Grimm & Mc-Sween 1993; Monteux et al. 2018) as well as later collisional losses (Genda & Abe 2005; Marcus et al. 2010).

In this *Letter* we use dynamical simulations to show that the migration model produces a broad diversity in the compositions of super-Earths. In many systems, the closest-in planets are rocky. In some cases Earth-sized rocky planets survive on orbits exterior to those of ice-rich planets. The feeding zones of close-in planets are generally very wide and disconnected from their final orbital locations. We illustrate these ideas using a simulation that produced a remarkably good analogue to the Kepler-36 system of two planets on very close orbits with very different densities (Carter et al. 2012).

2 SIMULATION SETUP

Our simulations are based on the model of Izidoro et al. (2017). We now summarize the main ingredients.

We used the disc structure and evolution model of Bitsch et al. (2015). The gaseous disc evolved viscously over its 5.2 Myr lifetime, with a rapid final dissipation over the last 0.1 Myr (for details see Izidoro et al. 2017). Migration was calculated using the torque formulae from Paardekooper et al. (2010), Paardekooper, Baruteau & Kley (2011) for our disc model including a correction to the corotation torque associated with the embryos' eccentricities (Bitsch & Kley 2010; Cossou, Raymond & Pierens 2013; Fendyke & Nelson 2014). Migration may be directed either inwards or outwards depending on a planet's mass and its location within the disc (see Bitsch et al. 2013, 2014, 2015). Type I damping of eccentricities and inclinations (Papaloizou & Larwood 2000; Tanaka & Ward 2004) was included using the equations of Cresswell & Nelson (2008). The integrator is based on the MERCURY hybrid symplectic integrator (Chambers 1999). Collisions were treated as inelastic mergers.

Our simulations started from a range of distributions of planetary embryos, assumed to have formed by planetesimal or pebble accretion (Kokubo & Ida 2002; Ormel & Klahr 2010; Lambrechts & Johansen 2012; Morbidelli et al. 2015). We included $25-40 M_{\oplus}$ in planetary embryos, with a division between rocky and icy bodies at 5 AU (the location of the snowline at the start of the disc's evolution Bitsch et al. 2015). Rocky embryos contained 20-40 per cent of the total embryo mass. In some cases, rocky embryos were given randomly chosen masses from $0.1\text{--}0.5\,M_\oplus$ while icy embryos had masses of 0.5–4.5 M_\oplus and in other simulations all embryos were given masses of 0.5–4.5 M_{\oplus} . This therefore encompasses both a scenario in which no rocky embryos migration and one in which they do. Rocky embryos were placed beyond 0.7 AU; in some cases in a relatively narrow annulus and sometimes in a broad disc. The total number of embryos was 20-40, with a similar number of rocky and icy bodies. All bodies were given small random initial inclinations



Figure 1. Orbital (top panel) and mass (bottom) evolution of a simulation that produced two close-in planets reminiscent of the Kepler-36 system. All bodies incorporated into a given planet have the same colour such that each planet's feeding zone can be inferred from the original orbital distance of its components. The disc dispersed after 5.2 Myr as indicated by the dashed line. An animation of the simulation can be viewed at http://youtu.be/uEK6FTj6s7c.

of up to 1° and eccentricities of up to 0.01. For calculating radii (to determine collisions), rocky and icy embryos were given different bulk densities, in some cases of 3 and 1.6 g cm⁻³, respectively, and in other cases 5.5 and 2 g cm⁻³. In addition to the variations in initial embryo location, we changed the disc's metallicity *Z* between 0.25 and 1 per cent, which affects the disc's temperature structure and the associated migration map (Bitsch et al. 2015). We ran 95 simulations, each integrated for 5–50 Myr beyond the disc's dispersal.

3 FORMATION OF A KEPLER-36 ANALOGUE

Fig. 1 shows the evolution of a particularly interesting simulation. The simulation started with six ice-rich embryos between 5 and 8.2 AU with masses from 2 to 4.2 M_{\oplus} for a total of $20 M_{\oplus}$, and 13 rocky embryos from 0.7 to 1.2 AU with masses from 0.1 to 0.45 M_{\oplus} for a total of $3.75 M_{\oplus}$. As ice-rich embryos migrated inwards, some rocky embryos were accreted and others were scattered outwards. The remainder of the rocky material was shepherded inwards by inner resonances with the innermost migrating icy embryo; first by the 8:5 and later by the 3:2 and 5:4 resonances. This inward-shepherded material was compressed into a narrow radial zone and grew rapidly by collisions into a single, $3 M_{\oplus}$ rocky planet.

After roughly 1 Myr, the region of outward migration in the disc shifted to encompass the growing planets due to the evolution of the disc itself (see Fig. 2; in this case the disc's metallicity was 0.5 per cent).¹ This quickly triggered a collision between the

¹We note that the outward migration of embryos had little effect in the simulations of Izidoro et al. (2017), mainly because of the modestly higher



Figure 2. Two snapshots of the system's evolution, superimposed on the disc's migration map. The grey curves show the zero-torque (no migration) zone. Within the grey contours (i.e. for $2-4 M_{\oplus}$ planets out to ~ 3 AU in the bottom panel) migration is directed outwards. Migration is directed inward everywhere else in mass–orbital distance space. In the top panel, all of the embryos migrate inwards. In the bottom panel, only the large inner ice-rich embryo feels a negative (inwards) torque from the disc, but it holds back the outward migration of the innermost rocky embryo.

two innermost icy embryos to form a $7.3 \, M_{\oplus}$ icy planet. This increase in mass was sufficient to push the planet back towards inward migration. All of the other planets felt positive torques. The outer planets migrated out towards the zero-torque location, but the innermost rocky planet's outward migration was blocked by the inwardmigrating large icy planet. This convergent migration pushed the planets towards successively closer resonances, and they ended up locked in 7:6 resonance. This was demonstrated by the libration of the resonant angle $\Theta_1 = 7 \lambda_2 - 6 \lambda_1 - \varpi_1$, where λ_1 and λ_2 are the inner and outer planets' mean longitudes, respectively, and $\overline{\omega}_1$ is the inner planet's longitude of pericentre. The planets survived in resonance after the disc dissipated, to the end of the simulation. Meanwhile, the three outward-migrating icy embryos reached the zero-torque radius and ended up in a 1:2:3 resonant chain. Two additional rocky embryos were shepherded outwards and eventually collided with the icy embryos.

planet masses. This put the super-Earths firmly in the inward migration regime, above the outward-migration zone depicted in Fig. 2. However, Raymond et al. (2016) proposed that Jupiter's core formed close-in and migrated outwards.

The planets' feeding zones can be inferred from Fig. 1, as all of the building blocks of each surviving planet have the same colour. The rocky planet formed from the collisional growth of nine terrestrial embryos, all of which originated between 0.7 and 1.1 AU. Most of the four surviving icy planets' masses originated in the icy region from 5 to 10 AU. Three of the four accreted 1–2 rocky embryos but these accounted for just 3–6 per cent of their final masses.

The two inner planets present an intriguing analogue to the Kepler-36 system. The Kepler-36 system contains two planets with well-constrained radii and masses (Carter et al. 2012). Kepler-36b has a mass of $4.5 \,M_{\oplus}$ and a radius of $1.49 \,R_{\oplus}$ for a mean density of 7.46 g cm⁻³, clearly within the rocky regime and consistent with the same composition as Earth. In contrast, Kepler-36c has a mass of $8 \,M_{\oplus}$ and a radius of $3.7 \,R_{\oplus}$ for a bulk density of 0.9 g cm⁻³, indicating that it must have a significant gaseous envelope accounting for 1–10 per cent of its mass (Carter et al. 2012). The planets' orbital radii are 0.115 and 0.128 AU and they have a period ratio of 1.173, placing them very close to the 7:6 resonance. Numerical integrations suggest that their orbits are chaotic with a very short Lyapunov time (Deck et al. 2012).

Our two close-in simulated planets have drastically different feeding zones that may, by analogy, explain the very different radii of the Kepler-36 planets. The inner (lower-mass) planet is purely rocky and should have a composition and bulk density similar to Earth, as is the case for Kepler-36b. The outer (higher-mass) simulated planet is mostly icy. While we do not model gas accretion and evaporation or radius evolution, the outer planet is more likely than the inner planet to have accreted a gaseous envelope because of its larger mass and longer time spent embedded within the disc, especially when the disc was at its densest (see e.g. Ikoma, Emori & Nakazawa 2001).

Our simulations also provide a decent match to the orbital architecture of the system. The simulated planets are locked in 7:6 resonance but their exact orbital period oscillates between 1.158 and 1.174, encompassing the Kepler-36 value of 1.173 and spending \sim 20 per cent of their time within 0.001 of the true value. There are some small differences: the simulated planets are 30 per cent farther from their star, with the innermost planet at 0.15 AU. The mass ratio of our simulated planets is 2.4, slightly higher than the real system's value of 1.8.

The origin of the density difference between the Kepler-36 planets has been attributed to photoevaporation, which is much more efficient for planets with lower-mass cores (Lopez & Fortney 2013). Yet we have shown that drastic density differences between adjacent planets may also occur as a result of migration within the disc, with orbital configurations just as compact as the Kepler-36 system.

4 DIVERSITY OF OUTCOMES

Fig. 3 shows the final configuration of 10 simulations that illustrate the diversity of outcomes produced by the migration model. Here we have assumed that objects originating past the snowline (at 5 AU at the start of the simulations) are 50–50 rock–ice mixtures and those originating closer-in are pure rock. In many of these systems the innermost planets are purely rocky. This emphasizes our main point that even if icy embryos migrate inwards the innermost planets may still be rocky. In one system the five innermost planets are rocky. Of course, in many systems the innermost planet is dominated by mass by an embryo that migrated inwards from past the snowline. In some systems rocky planets survived on orbits exterior to the icy embryos (Fig. 3). In some long resonant chains, rocky planets are scattered throughout the chain. In systems with more widely



Figure 3. Final configuration of 10 simulations illustrating the range of outcomes. Each planet's colours represent its rough composition: grey indicates rock and blue represents ice. Embryos that started past 5 AU started as 50-50 rock–ice mixtures and those from inside 5 AU were purely rocky. We do not account for various water loss processes and so the ice contents of simulated planets are certainly overestimates. The sizes of planets are scaled to their mass^{1/3}. The Kepler-36 analogue system from Section 3 is at the top. Two coorbital systems are marked with an asterisk.

spaced orbits rocky planets are less common. Most of these systems formed resonant chains that later became unstable (as in Izidoro et al. 2017) and the rocky planets collided with icy ones. Two of the systems from Fig. 3 contain coorbital planets, a common outcome of migration (Cresswell & Nelson 2009).

The water contents of simulated planets from Fig. 3 are likely overestimated. While cosmic abundance would suggest that icy embryos should form as 50-50 ice-rock mixtures (Lodders 2003), thermal and collisional processes may reduce the ice fraction. The constituent planetesimals of migrating ice-rich embryos form very early, leading to strong heating from short-lived radionuclides and dehydration (Grimm & McSween 1993; Monteux et al. 2018). Giant impacts may preferentially strip outer, icy mantles or surface oceans (Genda & Abe 2005; Marcus et al. 2010). However, upon inspection of the impacts suffered by super-Earths in our simulations we find that most impacts were relatively gentle, with collision speeds just above the two-body escape speed. Only a very small fraction of impacts was energetic enough to strip more than 10-20 per cent of the super-Earths' water (following Marcus et al. 2010). This implies that late collisional losses are not likely to drastically alter the rock/water ratio.

5 LIMITATIONS OF OUR WORK

Our simulations are admittedly simple. There are large uncertainties (and likely a large variety; Bate 2018) in the structure and evolution of planet-forming discs (see Morbidelli & Raymond 2016). We have chosen a single, albeit reasonable disc model (Bitsch et al. 2015). We have not accounted for the fact that the disc's water content itself has a strong impact on embryos' migration and accretion histories (Bitsch & Johansen 2016). Our simulations do not include processes that may be important for the formation of super-Earths, notably pebble accretion (Ormel & Klahr 2010; Lambrechts & Johansen 2012) and gas accretion/erosion (Ginzburg, Schlichting & Sari 2016). Our initial conditions are reasonable extrapolations of current models of embryo growth (Kokubo & Ida 2002; Morbidelli et al. 2015) but those models are themselves highly dependent on

6 DISCUSSION

The prevalence of rocky versus icy super-Earths is a potential discriminant of planet formation models (Raymond et al. 2008). Of course, the closest-in planets are easiest to characterize (via bulk density measurements; e.g. Marcy et al. 2014). Planets in the 'photoevaporation valley', at small masses very close to their stars, have recently been interpreted as being rocky in nature (Lopez 2017; Owen & Wu 2017; Jin & Mordasini 2018). The dip in planet occurrence between ~1.5 and $2 R_{\oplus}$ (Fulton et al. 2017) has also been interpreted as an indicator that many close-in planets are rocky (Van Eylen et al. 2017; Jin & Mordasini 2018).

Our results serve to inject caution into the discussion. We have demonstrated that the inward migration of ice-rich embryos often acts to catalyse the growth of pure rock planets. The existence of very close-in rocky super-Earths cannot be used as evidence against the migration model. It is even possible that planets originating past the snowline contain far less water than generally assumed. Strong radiogenic heating should completely dehydrate fast-growing planetesimals (Grimm & McSween 1993; Monteux et al. 2018), yet planetesimals past the snowline should continue to accrete icy pebbles. The giant impacts in our simulations were not energetic enough to produce strong water/ice loss. We conclude that further studies are needed to assess the water retention/loss on super-Earths that form beyond the snowline. Nonetheless, it is hard to imagine the migration model producing only rocky super-Earths, unless a mechanism exists to preferentially produce large (migrating) rocky embryos rather than icy ones.

Our Kepler-36 analogue simulation illustrates how adjacent planets can have drastically different feeding zones. In the face of migration, planets' feeding zones are often very wide and disconnected from their final orbital locations. The rocky Kepler-36b analogue accreted entirely from embryos between 0.7 and 1.1 AU but ended up at 0.15 AU (see Fig. 1). Likewise, the ice-rich Kepler-36c analogue finished the simulation at 0.17 AU but accreted mainly from embryos that originated past 5 AU. The large density difference between the Kepler-36 planets may plausibly be explained as a result of the system's formation process.

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