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Theoretical predictions of mass, semimajor axis and eccentricity distributions of super-Earths

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Abstract. We discuss the effects of close scattering and merging between planets on distributions of mass, semimajor axis and orbital eccentricity, using population synthesis model of planet formation, focusing on the distributions of close-in super-Earths, which are being observed recently. We found that a group of compact embryos emerge interior to the ice line, grow, migrate, and congregate into closely-packed convoys which stall in the proximity of their host stars. After the disk-gas depletion, they undergo orbit crossing, close scattering, and giant impacts to form multiple rocky Earths or super-Earths in non-resonant orbits around ~ 0.1AU with moderate eccentricities of ~ 0.01–0.1. The formation of these planets does not depend on model parameters such as type I migration speed. The fraction of solar-type stars with these super-Earths is anti-correlated with the fraction of stars with gas giants. The newly predicted family of close-in super-Earths makes less clear "planet desert" at intermediate mass range than our previous prediction.

Keywords. planets and satellites: dynamical evolution and stability, planets and satellites: formation, planetary systems: protoplanetary disks

1. Introduction

A radial velocity survey suggests that 40–60% of solar-type stars bear super-Earths with mass up to $\sim 20M_\oplus$ and period up to 50 days and in many cases these super-Earths are members of multiple-planet systems (e.g., Mayor *et al.* 2009; Bouchy *et al.* 2009; Lo Curto *et al.* 2009). From a radial velocity survey for a controlled sample, Howard *et al.* (2010) derived a planetary mass function around solar-type stars. They found that about 12% and 7% of stars have close-in plantes in mass ranges of 3-10$M_\oplus$ and 10-30$M_\oplus$, respectively. The function monotonically decreases with planetary mass, not showing any deficit in intermediate masses ("planet desert") that theorectical simulations predicted (1-50$M_\oplus$ by Ida & Lin 2004a, 2008a; 1-10$M_\oplus$ by Mordasini *et al.* 2009b). Kepler transit survey also suggests non-existence of "planet desert" for close-in planets (Borucki *et al.* 2010).

Based on the conventional core accretion scenario, we constructed a population-synthesis planet formation model (Ida & Lin 2004a, 2004b, 2005, 2008a, 2008b). In the model, we derived prescriptions for coagulation of planetesimals to form rocky planetary embryos and icy/rocky cores, gas accretion onto the cores, and orbital migration of embryos and gas giants, from detailed simulation results. Mordasini *et al.* (2009a, b) constucted a similar model. All these models have neglected planet-planet interactions.

However, even with a modet amout of type I migration, embryos would migrate toward their host stars. Resonant trapping, close scattering, and collision would play an important role in the final configuration of close-in rocky planets. Gravitational perturbations by gas giants should also sculpture planetary systems as a whole. Here, we briefly summarize related N-body simulations, modeling of the N-body simulation results for population synthesis calculations, and the effects of planet-planet dynamical interactions on the predicted distributions of extrasolar planets, focusing on close-in super-Earths.

2. N-body simulations on formation of close-in super-Earths

Ogihara & Ida (2009) performed N-body simulation to study the accretion of planets from planetesimals near the disk inner edge. Inward type I migration of planets is halted either by truncation of gas at the disk edge or by resonant perturbation from an inner planet. They found that in the case of relatively slow type I migration, 20–30 planets are captured by mutual mean-motion resonances and extend from the disk inner edge to the regions well beyond 0.1AU. After disk gas depletion, these planets start orbit crossing and giant impacts, resulting in formation of several close-in super-Earths. The super-Earths thus formed are kicked out of resonances by strong scattering and collisions. This is in contrast to the fast migration case in which only several planets survive during the presence of the gas and they remain in stable resonant orbits even after disk gas is removed (Terquem & Papaloizou 2007; Ogihara & Ida 2009).

3. N-body simulations on formation of eccentric jupiters and close-in retrograde jupiters

Many of extrasolar gas giants so far discovered have large eccentricities (> 0.2). One of promising excitation mechanisms is orbital instability between gas giants called “jumping jupiter” process (e.g., Rasio & Ford 1996; Marzari & Weidenschilling 2000). After the disk gas depletion, secular perturbations among gas giants lead to their orbital crossing. Close scatterings usually result in ejection of one planet, leaving other giants in well-separated stable eccentric orbits. Secular perturbations from the giant planets in eccentric orbits may destabilize orbits of rocky and icy planets in board regions. The eccentricity distribution created by the scattering may be consistent with observed one (e.g., Chatterjee *et al.* 2008; Juric & Tremaine 2008).

The jumping jupiter process also forms close-in hot jupiters if it is combined with Kozai mechanism and tidal dissipation (Nagasawa *et al.* 2008). Nagasawa *et al.* (2008) found that in 30% of runs of N-body simulations the eccentricity of an inwardly scattered giant is further increased enough for tidal circularization by Kozai mechanism from outer giants that often have high inclinations acquired by mutual close scattering. The circularized probability of $\sim 30\%$ is one order of magnitude higher than that in the case of only two giants and that found only in final state of three giants case.

They also predicted that many of the circularized planets have retrograde orbits. When the eccentricity of the inner planet becomes close to unity, its orbital angular momentum is so low that small perturbations from the outer planets can easily makes the orbit retrograde. This prediction is consistent with recent Rossiter-MacLaughlin measurements.

These N-body simulations show that planet-planet interactions are important factors to configure orbital distributions of extrasolar gas giants as well as type II migration.

4. Modeling to planet-planet dynamical interactions

Ida & Lin (2010) constructed a prescription that approximates the process of eccentricity excitation and collisions (giant impacts) of rocky planetary embryos in gas free environment, which is briefly summarized as follows: 1) evaluate the timescale for embryo pairs to start orbit crossing ($\tau_{\rm cross}$) and identify the pair with the shortest $\tau_{\rm cross}$, 2) after such a time interval has elapsed, compute the expected statistical changes in their eccentricity and semimajor axis, and then identify all other embryos whose orbits would cross this pair, if these changes were implemented, 3) for this group of embryos, implement statistical changes in e and a due to repeated close scattering among themselves, preserving the conservation of total orbital energy, 4) identify pairs of impacting embryos based on their statistically weighted collisional probability, and 5) under the assumption that these events lead to cohesion, adjust both a and e of the merger product to satisfy the conservation of total Laplace-Runge-Lenz (LRL) vector. Although these comprehensive procedures are complicated to integrate, each step is based on well-studied celestial mechanics. Other than two empirical parameters, there is no need to introduce any arbitrary assumptions. The two parameters are also qualitatively inferred from celestial mechanics.

They found that the above prescription reproduces quantitative statistical properties of mass, semimajor axis and eccentricity distribution of final planets obtained in N-body simulations by Kokubo *et al.* (2006). Because this process itself includes chaotic features and the prescription includes Monte Carlo approach, comparison is meaningful only for statistical quantities such as mean values and their dispersion of physical quantities.

Ida & Lin (2010) found that a collision occurs only when an inner planet is near its apoastron and an outer one is near its periastron and such a collision results in small eccentricity of the merged body due to conservation of total LRL vector. As a result, eccentricities of final planets are usually much smaller than those during orbital crossing that are determined by surface escape velocity of the interacting planets. This demonstrates that this kind of modeling can reveal intrinsic physics that is not usually revealed by full simulations, such as N-body simulations.

They also showed that $\tau_{\rm cross}$ jumps up by orders of magnitude at every merging event, because $\tau_{\rm cross}$ increases with orbital spacing scaled by Hill radius and decrease in orbital eccentricity. Through repeated merging events on timescales of 10^7–10^8 years, the system eventually reaches a state with $\tau_{\rm cross}$ longer than main-sequence lifetime of solar-type stars.

Nagasawa & Ida (2011) derived a prescription to predict the final states of the jumping jupiter process. Since scatterings between gas giants have sufficient ability to eject planets from the systems, stable orbits are realized by ejection rather than merging. Since ejcetion dereases number of bodies, ejection also drastically increases $\tau_{\rm cross}$. In the case of three planets, only one ejection event is enough to raise $\tau_{\rm cross}$ over main-sequence lifetime of solar-type stars. Each step of this process is also based on well-studied celestial mechanics. Their results also quantitatively reproduce statistical features of N-body simulations.

5. Eccentricity trap

The coagulation of embryos to form close-in super-Earths sensitively depends on how migration of embryos is halted near the disk inner edge. In N-body simulation by Ogihara & Ida (2009), the innermost embryo is pinned to the disk inner edge (set at ~ 0.05AU) and 20–30 resonantly trapped embryos extend from the edge to the regions well beyond 0.1AU, in the slow migration case. Because the inner edge may correspond to the corotation radius with the host star's spin, tidal force from the host star does not decay these embryo orbits outside the disk inner edge. Consequently, the super-Earths which form through the giant impacts are distributed at $\sim$ 0.05–0.2AU in their simulations, which may be consistent with observed data.

If the innermost embryo were pushed inward into the inner cavity by torques from outer embryos, its orbit would be tidally decayed. Then, since many embryos are not retained and the embryo masses are usually smaller than the Earth mass, super-Earths are not formed from coagulation of these retained embryos in this case.

Because individual embryos are losing angular momentum through type I migration and the angular momentum is redistributed throughout the convoy with resonant interactions, large amount of angular momentum must be supplied to prevent the embryos from penetrating the disk edge. Ogihara *et al.* (2010) investigated this issue through orbital integration and analytical arguments. If the innermost planet has such large eccentricity that radial excursion is larger than width of inner disk edge, the planet suffers eccentricity damping due to disk-planet interaction only near the periastron. Then, the damping expands its orbit (increases semimajor axis). The eccentricity damping is fast enough to compensate for the angular momentum loss of all the outer embryos due to type-I migration. Because this mechanism requires continuous eccentricity excitation of the innermost planet, it works for comparable-mass embryos that are resonantly interacting with each other. Ogihara *et al.* (2010) called this mechanism as “eccentricity trap.”

6. Formation of close-in planets

Using the prescription for giant impacts of rocky embryos and the “eccentricity trap” found by Ogihara *et al.* (2010), Ida & Lin (2010) systematically studied the formation process of non-resonant multiple close-in super-Earths found by Ogihara & Ida (2009).

Figure 1 shows an exmple of the integration of growth and migration of planets in a disk with a modest initial mass (2.5 times as massive as the minimum-mass solar nebula) and migration efficiency $C_1 = 0.1$, which is a scaling factor for type I migration defined by $\dot{a} = C_1 \dot{a}_{\rm Tanaka}$ where $\dot{a}_{\rm Tanaka}$ is migration rate derived by Tanaka *et al.* (2002). Seed

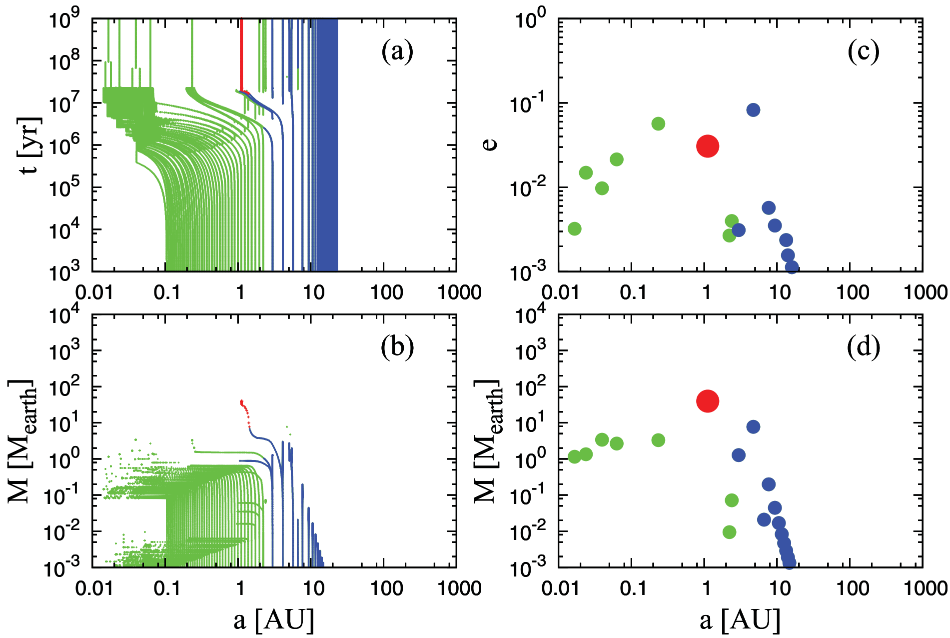

Figure 1. An example of integration of growth and migration of planets from a disk 2.5 times more massive than the minimum-mass solar nebula. (a) Time evolution, (b) mass evolution, (c) final eccentricities, and (d) final masses.

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embryos are distributed at 0.1–30AU and are integrated including mutual dynamical interactions. Embryos' migration is stalled by "eccentricity trap" at the disk inner edge (at ~ 0.04AU).

In inner regions, embryo growth due to planetesimal accretion and their migration are so fast that they form a swarm of embryos trapped in mutual mean-motion resonances in the proximity of the host star (Figure 1a). Because type I migration is faster and embryo growth is slower for more massive bodies, type I migration is dominated for embryo masses larger than critical masses, $M_{\rm c,crit} \sim 0.1$–$1 M_\oplus$ (Figure 1b). Beyond an ice line, an icy core grows up to $\sim 10 M_\oplus$ and starts runaway gas accretion. In outermost regions, planetesimal growth is so slow that only small planets emerge (planets at < 5AU are ejected by the gas giant).

The mass, semimajor axis and eccentricity of final planets are plotted in Figure 1c and d. The innermost four planets have grown through giant impacts after gas depletion. Since a collision disspipates only a fraction of orbital energy, the resultant semimajor axis of the merger products is comparable to that of their progenitor embryos. In the absence of residual disk gas, these merger products do not undergo any further orbital decay and generally remain out of mean motion resonance with each other.

The velocity dispersion of the residual embryos is a fraction of their surface escape velocity. In the stellar proximity, it is much smaller than the local Keplerian velocity. Thus, the simulated eccentricities of close-in super-Earths are relatively small (~ 0.01–0.1).

The largest planet in the innermost region has mass more than $5 M_\oplus$. Since this planet acquired most of its mass after the gas is depleted, it cannot accrete a substantial gaseous envelope. The atmosphere of their progenitor embryos may also be ejected during giant impacts. This explains why some of the discovered super-Earths have masses larger than $10 M_\oplus$ without becoming gas giants.

Although $C_1 = 0.1$ is adopted in the result of Figure 1, the statistical properties of formed close-in super-Earths/Earths does not depend sensitively on C_1 unless it is too small ($C_1 < 0.01$) to bring many embryos to the proximity of the host star. Since the trapped embryos stay in stable orbits until disk gas severely decays, the results do not depend on how fast the emryos migrated to the proximity of the host star.

7. Population synthesis

Ida & Lin (2011) performed population synthesis simulation including the prescriptions for dynamical interactions between gas giants (Nagasawa & Ida 2011), in addition to the effect of giant impacts of rocky embryos (Ida & Lin 2010). In Figure 2, mass, semimajor axis, and orbital eccentricity of all the planets formed in 3000 disks are superposed. The mass of stellar mass are logarithimically ramdopmly chosen between $0.8 M_\odot$ and $1.25 M_\odot$, and it is assumed that disk masses ($M_{\rm disk}$) follow a log normal distribution centered at $\log(M_{\rm disk}/M_\odot) = -2$ with dispersion of 1 (Ida & Lin 2008a). Exponential decay of disk gas surface density with depletion timescale of 3 Myrs is assumed for all the disks. Ida & Lin (2011) followed Ida & Lin (2010) for the setting of seed planets and integration of planetesimal accretion and embryo's type I migration and followed Ida & Lin (2008a) for gas accretion rate onto planets and type II migration of gas giants, except a prescription for truncation of the gas accretion in a dissipating disk. The gas accretion rate onto a planet is limited by disk gas accretion rate, rather than more severe truncation condition with local depletion that was adopted in Ida & Lin (2008a).

Although eccentricity distributions of gas giant planets (Figures 2a and c) are important, we here focus on distributions of close-in super-Earths, which are based on the

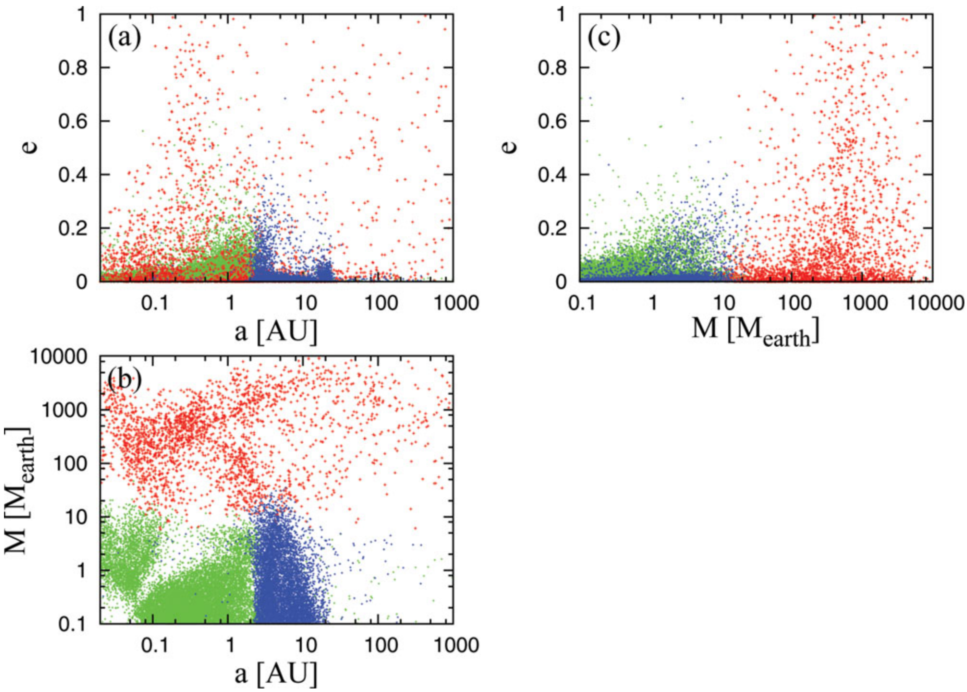

Figure 2. Distributions of simulated planets from 3000 disks on (a) eccentricity (e) - a plane, (b) semimajor axis (a) - mass (M) plan, and (c) e - M plane.

prescription in Ida & Lin (2010). In Figure 2b, a new pronounced population is found at $M \sim 1$–$10 M_\oplus$ and $a \sim 0.03$–0.15AU that did not exist at all in the previous simulations without dynamical interactions (e.g., Ida & Lin 2008). These close-in super-Earths are formed by the mechanism described in section 6. The eccentricities of these super-Earths are small (< 0.1).

Figure 3 shows dependence on C_1. Frequency of gas giants decreases sensitively with C_1, because for larger values of C_1, it is more difficult to form cores larger than a critical core mass of $>$ several $M_\oplus$ for the onset of runaway gas accretion (Ida & Lin 2008).

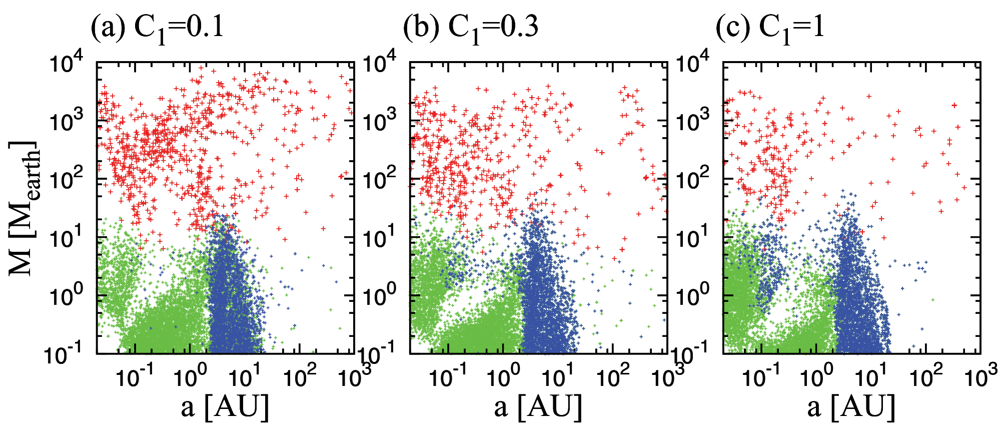

Figure 3. Distributions of simulated planets from 1000 disks on semimajor axis (a) - mass (M) plane for (a) $C_1 = 0.1$, (b) $C_1 = 0.3$, and (c) $C_1 = 1$.

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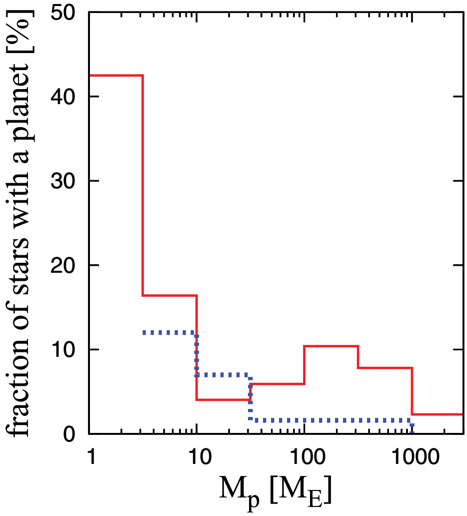

Figure 4. Fraction of stars harboring planets with corresponding masses and periods less than 50 days. Solid and dashed lines express our theoretical result in Figure 2 and observational data by Howard *et al.* (2010).

On the other hand, frequency of close-in super-Earths rather increases with C_1. The formation mechanism of close-in super-Earths in section 6 suggests that the frequency of these planets are almost independent of C_1. However, for smaller C_1, gas giants are more abundant and their perturbations destabilize orbits of super-Earths, so that surviving super-Earths are less abundant.

Since even in disks with not large initial dust-to-gas ratio, super-Earths can be formed from the accumulated embryos and there is no threshold mass like the critical core mass for runaway gas accretion, the dependence of frequency of super-Earths on host stars' metallicity would be much weaker than gas giants, which may be also consistent with observed data.

Figure 4 shows the fraction of stars harboring planets with corresponding masses and periods less than 50 days. Solid and dashed lines express our theoretical result in Figure 2 and observational data by Howard *et al.* (2010). The simulations including the dynamical interactions produce a new population of close-in super-Earths, so the fraction of stars with planets of $1–10M_\oplus$ is much more enhanced than that obtained in the simulations neglecting the dynamical interaction. However, the new result still shows a gap at $10–100M_\oplus$ ("planet desert"), while the observed data does not show any gap. We also note that the simulation overproduces hot jupiters with $> 30M_\oplus$. Hot jupiters could be disrupted by tide, evaporation or insufficient migration halting at the disk edge. If such disruption were included in our simulations, the theoretical result would become more consistent with the observed data.

8. Summary

The implement of planet-planet interactions into the population synthesis model enables use to predict eccentricity distributions and distant planets scattered outward. The planet-planet interactions also play an important role in assemblages of planetary embryos that have migrated from outer regions to the vicinity of the host stars. Here we described a scenario for formation of close-in multiple non-resonant super-Earths. Our model predicts ubiquity and weak dependence on stellar metallicity of these systems

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around solar-type stars and why they missed runaway gas accretion even if they have masses > several $M_\oplus$. We showed that the boundary condition at the disk edge plays an crucial role in the formation of these systems. For more reliable predictions, we need detailed investigation on evolution of the disk edge as well as the effects of tide and thermal evaporation.

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