

PLANET FORMATION AROUND LOW-MASS STARS: THE MOVING SNOW LINE AND SUPER-EARTHS

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ABSTRACT

We develop a semianalytic model for planet formation during the pre-main-sequence contraction phase of a low-mass star. During this evolution, the stellar magnetosphere maintains a fixed ratio between the inner disk radius and the stellar radius. As the star contracts at constant effective temperature, the “snow line,” which separates regions of rocky planet formation from regions of icy planet formation, moves inward. This process enables rapid formation of icy protoplanets that collide and merge into super-Earths before the star reaches the main sequence. The masses and orbits of these super-Earths are consistent with super-Earths detected in recent microlensing experiments.

Subject headings: planetary systems: formation — planetary systems: protoplanetary disks — stars: evolution — stars: formation

1. INTRODUCTION

The recent discoveries of super-Earths around low-mass stars challenge our understanding of planet formation. From separate microlensing events, Beaulieu et al. (2006) and Gould et al. (2006) provide strong evidence that planets with masses $M \sim 5\text{--}15 M_{\oplus}$ are common around M dwarf stars.¹ With orbital semimajor axes $a \sim 2.5\text{--}3$ AU, these planets are probably ice giants roughly similar in structure to Uranus and Neptune in the solar system.

Boss (2006) proposes that these planets form in two stages. After a disk instability produces a gas giant, photoevaporation of the gas giant atmosphere leaves behind an icy core with $M \sim 10\text{--}20 M_{\oplus}$. This mechanism requires a massive disk to initiate the instability and a nearby O-type star to photoevaporate the gas giant atmosphere. Boss notes that this process should yield (1) super-Earths around M dwarfs formed in rich star clusters and (2) gas giants around M dwarfs formed in low-mass stellar associations.

Beaulieu et al. suggest that super-Earths favor coagulation models, where collisions of 1–10 km objects eventually produce icy planets with $M \sim 10 M_{\oplus}$ at 1–10 AU. Although numerical calculations appear to preclude gas giants at 1–10 AU around M dwarfs (Laughlin et al. 2004), there has been no demonstration that coagulation produces icy planets on reasonable timescales in a disk around an M dwarf.

Here we develop a semianalytic coagulation model and show that contraction of the central star along a pre-main-sequence (PMS) Hayashi track sets the initial conditions for planet formation around low-mass stars. Our results indicate that icy protoplanets with $M \sim 0.1\text{--}1 M_{\oplus}$ form in $\sim 0.1\text{--}1$ Myr at 1–4 AU. Over 50–500 Myr, collisions between protoplanets produce super-Earths with masses similar to those detected in microlensing surveys.

¹ These microlensing observations directly yield the ratio M_p/M_* , where M_p is the mass of the planet and M_* is the mass of the star. Adopting the most likely parent star—a K dwarf or an M dwarf—yields the most likely M_p .

We start with the motivation for our study in § 2, discuss the coagulation model of planet formation and the moving snow line in § 3, develop the disk evolution model in § 4, and apply the model to super-Earth formation in § 5. We end with a brief summary in § 6.

2. MOTIVATION: PLANET FORMATION IN THE DISK OF A LOW-MASS STAR

To motivate our study, we contrast planet formation around low-mass stars and solar-type stars. For solar-type stars approaching the main sequence, the luminosity is roughly constant on typical planet formation timescales of 10–100 Myr. Thus, the conditions where planets form change little with time. For stars with masses $\leq 0.5 M_{\odot}$, however, the luminosity fades by a factor of 10–100 on the Hayashi track. Because the inner disk radius is “locked” at a fixed distance relative to the radius of the central star, the inner disk contracts as the star contracts. During this evolution, the “snow line”—the point that separates the inner region of rocky planet formation from the outer region of icy planet formation—also moves inward.

Coupled with the evolution of the inner disk, the moving snow line produces a dramatic variation in the surface density at fixed distances from the central star. This behavior enables the rapid formation of icy protoplanets. As the low-mass star approaches the main sequence, these protoplanets collide and merge into super-Earths with properties similar to those detected in recent microlensing experiments.

3. COAGULATION AND THE MOVING SNOW LINE

In coagulation models, planets grow from repeated collisions and mergers of small objects in a circumstellar disk (Safronov 1969). When 1–10 km “planetesimals” form and start to grow (Weidenschilling 1980; Dullemond & Dominik 2005), dynamical friction damps the orbital eccentricities of the largest objects. Damping yields large gravitational cross-sections and leads to “runaway growth,” where the largest objects grow fastest and

run away from more slowly growing smaller objects (Wetherill & Stewart 1989; Kokubo & Ida 1996). Throughout the runaway, the largest protoplanets stir up the leftover planetesimals. Eventually, the leftovers have orbital velocity dispersions comparable to the escape velocities of the largest protoplanets. Because gravitational cross-sections fall as velocity dispersions rise, runaway growth ends. The ensemble of planetesimals and protoplanets then enters “oligarchic” growth, where the largest objects—oligarchs—accrete at rates roughly independent of their size (Kokubo & Ida 1998).

During oligarchic growth, protoplanets become isolated from their surroundings. If an oligarch accretes all of the mass in an annulus with width $2BR_H$, where $R_H = a(M/3M_*)^{1/3}$ is the Hill radius, its isolation mass is

$$M_{\text{iso}} \approx 4\pi a B R_H \sigma \propto (B\sigma)^{3/2} a^3 M_*^{-1/2}, \quad (1)$$

where a is the orbital semimajor axis and σ is the mass surface density of solid material in the disk (e.g., Lissauer 1993; Kokubo & Ida 2000). If ρ is the mass density of a solid object, the timescale to reach isolation is (Goldreich et al. 2004)

$$t_{\text{iso}} \propto \rho^{1/2} a^{3/2} \sigma^{-1/2}. \quad (2)$$

In the solar system, oligarchic growth has two regimes. For $a \lesssim 3$ AU, planetesimals are rocky because volatile materials remain in the gas. In the “minimum-mass solar nebula” (MMSN; Weidenschilling 1977; Hayashi 1981) with $B = 2.5\text{--}5$, $\rho \sim 3$ g cm $^{-3}$, and $\sigma \sim 8$ g cm $^{-2}$ at 1 AU, $M_{\text{iso}} \sim 0.05\text{--}0.1 M_{\oplus}$. Once oligarchs contain $\sim 50\%$ of the total mass in solids, their mutual dynamical interactions lead to “chaotic” growth (Goldreich et al. 2004; Kenyon & Bromley 2006), where collisions between oligarchs eventually produce Earth-mass planets. Numerical simulations suggest that $\sim 10\text{--}20$ oligarchs collide to form a typical Earth-mass planet in $\sim 10\text{--}100$ Myr at 1 AU around a solar-type star (Chambers 2001; Raymond et al. 2004; Kenyon & Bromley 2006).

Outside the snow line, ice condensation enhances σ and promotes the formation of larger oligarchs. For $\rho \sim 1.5$ g cm $^{-3}$ and $\sigma \sim 3\text{--}6$ g cm $^{-2}$ at 5 AU, isolated oligarchs with $M_{\text{iso}} \sim 5 M_{\oplus}$ form on timescales $t_{\text{iso}} \sim 1\text{--}3$ Myr. These icy oligarchs accrete gas directly from the nebula and grow into gas giant planets in several megayears (Pollack et al. 1996), comparable to the lifetime of the gaseous disk (e.g., Hollenbach et al. 2000; Haisch et al. 2001; Young et al. 2004; Calvet et al. 2005).

For solar-type stars, planet formation is fairly independent of stellar evolution. Throughout most of the PMS phase, the solar luminosity is roughly constant. Thus, the position of the snow line— $a_{\text{snow}} \sim (L_*/T_{\text{snow}}^4)^{1/2}$, where L_* is the stellar luminosity and T_{snow} is the temperature where water and other volatile materials condense out of the gas—is roughly stationary in time. Because the $\sim 0.1\text{--}1$ Myr formation time for planetesimals and oligarchs is short compared to the ~ 10 Myr PMS lifetime, the separation between icy and rocky (proto)planets remains fairly distinct, evident in the composition of different populations in the asteroid belt (Abe et al. 2000; Rivkin et al. 2002). Although there is some mixing between water-rich and water-poor regions (Raymond et al. 2004), most chaotic growth occurs when the Sun lies close to the main sequence at nearly constant L_* .

In contrast with solar-type stars, stellar evolution is a crucial feature that defines the nature of newly formed planets around low-mass stars. Because the timescale for planetesimal and oligarch formation is short compared to the $0.1\text{--}1$ Gyr PMS

contraction time (D’Antona & Mazzitelli 1994; Baraffe et al. 1998; Siess et al. 2000), the timing of planetesimal formation sets the nature of icy/rocky planets with distance from a low-mass star. On its Hayashi track, the luminosity of a $0.25 M_{\odot}$ star fades by a factor of several hundred at roughly constant effective temperature. During this period, a_{snow} moves inward by a factor of $\sim 15\text{--}20$. Just outside the moving snow line, ice condensation increases σ (M_{iso}) by a factor of ~ 4 (8) (Hayashi 1981); t_{iso} decreases by a factor of 3. This moving snow line enables rapid formation of icy oligarchs that can collide and merge into super-Earths.

4. EVOLUTION OF A DISK AROUND A CONTRACTING STAR

Disk evolution is also an important feature of planet formation around low-mass stars. In the standard MMSN model, σ is fixed in time and scales with the stellar radius on the main sequence (e.g., Hayashi 1981). However, when PMS stars actively accrete from a circumstellar disk, magnetic interactions between the star and the disk appear to “lock” the inner disk radius R_{in} at a fixed distance relative to the stellar radius, $\xi \equiv R_{\text{in}}/R_* \sim 3$, at several megayears (e.g., Eisner et al. 2005). Although the duration of this phase is not well constrained, the observed change in ξ for disks around solar-type stars is a factor of $\sim 2\text{--}3$ (Eisner et al. 2005). If disks around low-mass stars remain locked for the entire PMS phase, the maximum decrease in the inner disk radius is a factor of $\sim 15\text{--}20$. This change is much larger than the observed variation of ξ ; thus, we assume $\xi = \text{constant}$. To conserve mass and angular momentum, σ and the outer disk radius must evolve, which impacts M_{iso} and the formation timescales for oligarchs and planets.

To construct a model for disk evolution, we adopt

$$\sigma(t) = \sigma_0 \frac{M_*}{M_{\odot}} f_{\text{ice}} \left[\frac{R_*(t)}{\beta a_{\text{AU}}} \right]^{3/2}, \quad (3)$$

where R_* is in units of solar radii, $\sigma_0 = 8$ g cm $^{-2}$, and a_{AU} is the radial distance from the star in AU. Setting the scale factor $\beta \sim 3$ yields the usual σ (MMSN) for a $1 M_{\odot}$ star at 1 Myr, when a large fraction of the solid mass in the terrestrial zone of the solar system is in large bodies. Consistent with observations (Natta et al. 2000; Scholz et al. 2006), we scale σ and the disk mass linearly with the stellar mass. For a 1 Myr old $0.25 M_{\odot}$ star, this scaled MMSN has $\beta = 2$ and $M_{\text{disk}} = 0.026 M_*$ integrated from $3R_*$ to 50 AU for a gas/solids ratio of 100. To provide a smooth transition from $f_{\text{ice}} = 1$ for $a \leq a_{\text{snow}}$ to $f_{\text{ice}} = 4$ for $a \geq a_{\text{snow}}$ (Hayashi 1981), we include a parameter $f_{\text{ice}} = 1 + (\Delta_{\text{ice}} - 1)/(1 + e^x)$, where $\Delta_{\text{ice}} = 4$, $x = (a_{\text{snow}} - a)/\Delta T_{\text{snow}}(a)$, and $\Delta T_{\text{snow}}(a)$ is the radial distance equivalent to a 5 K temperature change.

To derive a_{snow} , we adopt the temperature profile of a flat circumstellar disk, $T \propto T_*(R_*/a)^{3/4}$ (Kenyon & Hartmann 1987). We scale this relation to place the snow line at 2.7 AU at 1 Myr for a $1 M_{\odot}$ mass star, as inferred from analyses of water-rich objects in the outer asteroid belt (Abe et al. 2000; Rivkin et al. 2002). To evaluate $L_*(t)$, $R_*(t)$, and $T_*(t)$, we use PMS evolutionary tracks from Siess et al. (2000); other tracks (D’Antona & Mazzitelli 1994; Baraffe et al. 1998) yield similar results.

With these ingredients, we derive the evolution of σ , M_{iso} , and t_{iso} as the star contracts to the main sequence. This evolution has two main features. Initially, the snow line is at a large distance, $a_{\text{snow}} \sim 5$ AU, from the luminous PMS star. Inside $1\text{--}2$ AU, rocky oligarchs form and reach M_{iso} before the star

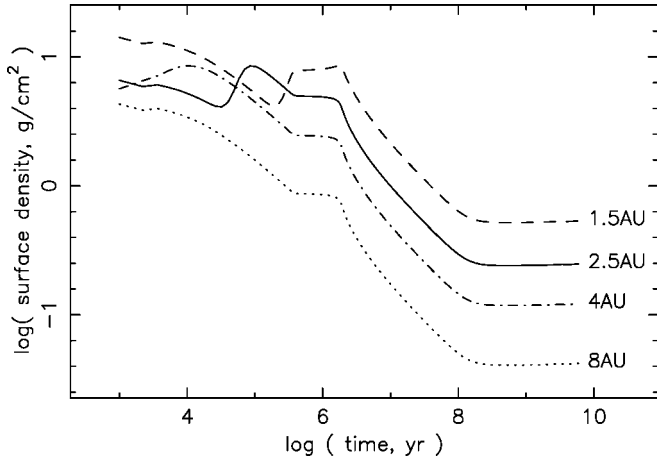


FIG. 1.—Surface density evolution at fixed radii around a $0.25 M_{\odot}$ star with $M_{\text{disk}}/M_{*} = 0.065$. As the snow line moves inward, ice condensation increases σ , which leads to faster formation of more massive oligarchs.

contracts significantly. Outside 1–2 AU, t_{iso} is long (eq. [2]) compared to the initial contraction time. As the star contracts, ices condense out of the nebula and the snow line moves inward. For $a \leq 1\text{--}2$ AU, this material coats the growing oligarchs, leftover planetesimals, and the surrounding debris with an icy veneer that may extend the oligarchic growth phase and produce more massive oligarchs. For $a \geq 1\text{--}2$ AU, ice condensation reduces t_{iso} by a factor of ~ 3 (eq. [2]), which enables the rapid formation of icy oligarchs well before the central star reaches the main sequence.

5. SUPER-EARTH FORMATION

To explore the consequences of this picture, we consider a disk with $\beta \sim 1$ ($M_{\text{disk}}/M_{*} = 0.065$), which lies at the upper end of the range inferred from observations² (Osterloh & Beckwith 1995; Nuernberger et al. 1997, 1998; Natta et al. 2000; Scholz et al. 2006). Figure 1 shows the σ evolution for this system at several distances from a $0.25 M_{\odot}$ star. For disks with other masses, $\sigma \propto M_{\text{disk}}$, $M_{\text{iso}} \propto M_{\text{disk}}^{3/2}$, and $t_{\text{iso}} \propto M_{\text{disk}}^{-1/2}$. Aside from the long-term decline in $\sigma(a)$ from PMS evolution, the σ evolution shows clear increases when the snow line crosses specific points in space and ices condense out of the gas. At these times, σ remains at a relatively constant plateau value for $\sim 1\text{--}3$ Myr before declining monotonically as the central star approaches the main sequence.

During the plateau phases, the timescale for oligarchs to reach $M_{\text{iso}} (\leq 1$ Myr; eq. [2]) is shorter than the stellar contraction time. Because the isolation masses at fixed distances decrease as σ decreases (eq. [1]), these early times provide the best opportunity for coagulation to form large protoplanets.

Figure 2 shows the time evolution of M_{iso} . Interior to a_{snow} ($a \leq 1\text{--}2$ AU), rocky oligarchs with $M_{\text{iso}} \sim 0.1 M_{\oplus}$ form in $\sim 10^5$ yr. As the star contracts, ice condensation enables the formation of larger oligarchs with $M_{\text{iso}} \sim 0.2 M_{\oplus}$ in ~ 1 Myr. At $a \sim 2\text{--}3$ AU, ice condensation during runaway growth promotes the formation of oligarchs with $M_{\text{iso}} \sim 0.5 M_{\oplus}$ in $\sim 10^5$ yr.

This analytic prescription for protoplanet growth suggests that oligarchs with $M_{\text{iso}} \sim 0.1\text{--}0.5 M_{\oplus}$ can form at $\sim 1\text{--}3$ AU in ≤ 1 Myr. If oligarchs contain roughly half the mass in solid

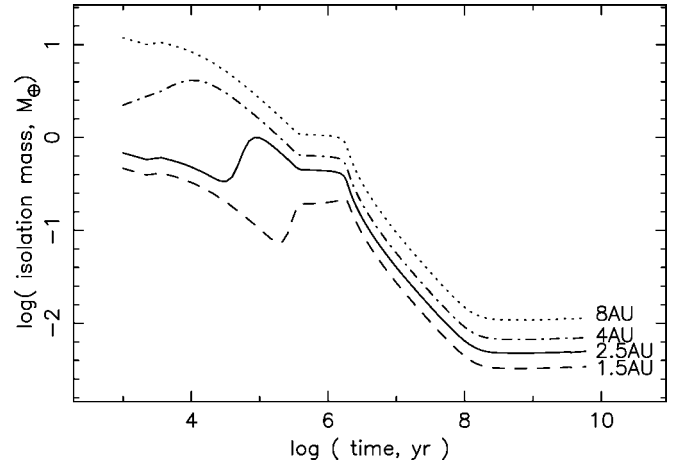


FIG. 2.—Evolution of M_{iso} at fixed radii using the σ evolution of Fig. 1. Ice condensation leads to more massive oligarchs at 2–8 AU in 1 Myr.

material at the onset of chaotic growth, our model disk with $\sim 5\text{--}10 M_{\oplus}$ at 1–4 AU will have $\sim 10\text{--}100$ oligarchs. The model predicts ~ 10 oligarchs at 2–4 AU. Thus, the building blocks for observable super-Earths can form on timescales much shorter than disk lifetimes derived from measurements of dust emission from low-mass PMS stars (Song et al. 2002; Weinberger et al. 2004; Liu et al. 2004; Plavchan et al. 2005).

To consider whether oligarchs can merge into super-Earths on reasonable timescales, we follow Goldreich et al. (2004) and introduce a parameter $\mathcal{R} = v_{\text{esc}}/\Omega a$, where v_{esc} is the escape velocity and Ωa is the orbital velocity of a growing planet. When $\mathcal{R} \ll 1$, colliding oligarchs merge; when $\mathcal{R} \gg 1$, collisions often eject an oligarch from the planetary system. At 1–5 AU around a $0.25 M_{\odot}$ star, this merger condition ($\mathcal{R} \lesssim 1$) allows the formation of $\sim 5 M_{\oplus}$ planets at 1–2 AU, $\sim 3 M_{\oplus}$ planets at 2–3 AU, and $1\text{--}2 M_{\oplus}$ planets at 3–4 AU. In this analytic model, the timescale to produce planets is ~ 200 Myr (1 Gyr) at 1 AU (5 AU).

To derive another estimate for the masses and formation timescales, we consider the results of complete numerical simulations of planet formation from an initial ensemble of oligarchs (Chambers 2001; Raymond et al. 2004) or planetesimals (Kenyon & Bromley 2006). In the solar terrestrial zone, collisions and mergers of 10–20 oligarchs with masses $\sim M_{\text{iso}}$ yield two to five planets with masses comparable to the mass of the Earth on timescales of 10–100 Myr. Although the final orbital parameters depend on the late-time evolution of the planetesimals and the gaseous disk, the typical masses and collision histories of Earth-mass planets are similar in all calculations and agree fairly well with analytic estimates. If we adapt this collisional history to a planetesimal disk around a $0.25 M_{\odot}$ star, mergers of ~ 10 oligarchs should yield planets with masses $\sim 1\text{--}2 M_{\oplus}$ at 1 AU and $\sim 3\text{--}5 M_{\oplus}$ at 2.5 AU.

When we combine the analytic and scaled numerical results, the timescale for oligarchs to merge into planets is roughly

$$t_{\text{merge}} \sim 10\text{--}100 \frac{8 \text{ g cm}^{-2}}{\sigma} \frac{P}{1 \text{ yr}} \text{ Myr}, \quad (4)$$

where P is the orbital period. Thus, the expected merger timescale for oligarchs at 1–3 AU around a $0.25 M_{\odot}$ star is $\sim 2\text{--}5$ times longer than for the terrestrial zone around a solar-type star. This timescale is comparable to the duration of the PMS contraction phase and is much shorter than the expected stellar

² In their coagulation model for Neptune, Goldreich et al. (2004) also consider a disk with $M_{\text{disk}} \sim (3\text{--}6) M_{\text{MMSN}}$.

lifetime. Thus, coagulation can produce super-Earths around low-mass stars on timescales of $\sim 50\text{--}500$ Myr.

In constructing our model, we adopted a standard surface density law, $\sigma \propto a^{-3/2}$, and ignored details of the disk structure (e.g., Davis 2005; Lecar et al. 2006) and physical mechanisms for ice condensation (e.g., Podolak & Zucker 2004). Although details of the disk structure and ice condensation mechanisms can affect the position of the snow line, our main conclusions that (1) a_{snow} moves considerably during the PMS contraction of a low-mass star and (2) ice condensation during the PMS contraction phase produces massive oligarchs in $\sim 0.1\text{--}1$ Myr and super-Earths in ~ 100 Myr, are generally independent of these details. The main uncertainties in our picture are the probability of the large initial disk mass and the details of the final accretion stage when $1\text{--}2 M_{\oplus}$ planets evolve into $3\text{--}5 M_{\oplus}$ planets. Observations of larger samples can yield better estimates for the range of initial disk masses for low-mass stars and for the $M_{\text{disk}}\text{--}M_{*}$ relation. Detailed numerical simulations can provide better estimates of the masses and formation timescales for super-Earths.

6. MODEL SUMMARY AND PREDICTIONS

We have developed an analytic prescription for planet formation by coagulation around low-mass stars. The model has two distinctive features that enable formation of super-Earths during the PMS contraction phase.

1. We set the inner disk radius at a fixed distance relative to the radius of the central star, $\xi \equiv R_{\text{in}}/R_{*}$. Thus, R_{in} changes as the star contracts to the main sequence, leading to significant evolution in $\sigma(a)$.

2. During PMS contraction, a_{snow} moves inward by a factor of $\sim 15\text{--}20$, producing large enhancements in $\sigma(a)$ as ices condense out of the nebula. Ice condensation is the key mechanism that allows coagulation to produce super-Earths around low-mass stars. This process results in new outcomes for planet formation, including planets with dense, rocky cores and thick, icy surfaces.

We applied this model to super-Earth formation around a $0.25 M_{\odot}$ star. At $1\text{--}5$ AU, isolated oligarchs can grow to masses $\sim 0.1\text{--}1 M_{\oplus}$ in $\sim 0.1\text{--}1$ Myr, short compared to the ~ 100 Myr PMS contraction time. These oligarchs merge into super-Earths with masses $\sim 2\text{--}5 M_{\oplus}$ as the star contracts to the main sequence. Thus, coagulation can produce planetary systems similar to those detected in recent microlensing events.

Aside from our success in producing icy super-Earths at $1\text{--}3$ AU around low-mass stars, the model makes clear predictions for rocky planet formation close to a low-mass star. At $a \lesssim 1$ AU, the isolation masses estimated for rocky planets are $M_{\text{iso}} \lesssim 0.01 M_{\oplus}$. If ~ 10 isolated objects merge into a rocky planet, we predict many low-mass planets with masses $\sim 0.1 M_{\oplus}$ at distances of $0.05\text{--}0.5$ AU around low-mass M dwarfs. We plan to explore the consequences of our model in future papers.

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