The Formation and Dynamics of Super-Earth Planets

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Abstract Super-Earths, objects slightly larger than Earth and slightly smaller than Uranus, have found a special place in exoplanetary science. As a new class of planetary bodies, these objects have challenged models of planet formation at both ends of the spectrum and have triggered a great deal of research on the composition and interior dynamics of rocky planets in connection to their masses and radii. Being relatively easier to detect than an Earth-sized planet at 1 AU around a G star, super-Earths have become the focus of worldwide observational campaigns to search for habitable planets. With a range of masses that allows these objects to retain moderate atmospheres and perhaps even plate tectonics, super-Earths may be habitable if they maintain long-term orbits in the habitable zones of their host stars. Given that in the past two years a few such potentially habitable super-Earths have in fact been discovered, it is necessary to develop a deep understanding of the formation and dynamical evolution of these objects. This article reviews the current state of research on the formation of super-Earths and discusses different models of their formation and dynamical evolution.

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1 INTRODUCTION

The discovery of planets around other stars has undoubtedly revolutionized our understanding of the formation and dynamical evolution of planetary systems. The diverse and surprising characteristics of these objects, both in orbital configuration and physical properties, have confronted astronomers with many new challenges and have reinvigorated the fields of planet formation and dynamics.

One surprising characteristic of the currently known extrasolar planets is the range of their masses. Unlike in the Solar System, where planets belong to two distinct categories of terrestrial (with masses equal to that of Earth or slightly smaller) and giant \([\sim 14 \text{ Earth masses } (M_\oplus) \text{ and larger}]\), many extrasolar planets have masses in an intermediate range, from slightly larger than Earth to 10 \(M_\oplus\). Dubbed super-Earths, these objects present a new class of planetary bodies with physical and dynamical properties that for the past few years have been the focus of research among many planetary scientists.

The first super-Earth around a main sequence star was discovered by Rivera et al. (2005) using the radial velocity technique. [Note that in 1992, Wolszczan & Frail (1992) discovered at least two terrestrial-class planets around the pulsar PSR 1257+12.] Thanks to ground-based observational projects such as the HARPS Search for Southern Extrasolar Planets\(^1\), the California Planet Survey (CPS)\(^2\), the Lick-Carnegie Exoplanet Survey (LCE), M2K (Clubb et al. 2009), and the MEarth Project (Nutzman & Charbonneau 2008; Irwin et al. 2009a,b)\(^3\), and the ongoing success of the CoRoT\(^4\) and Kepler\(^5\) space telescopes, to date, the number of these objects has exceeded 90. Tables 1 and 2 show the masses and orbital elements of the currently known super-Earths. As shown, the vast majority of these objects have orbital periods smaller than 50 days. A survey of the parent stars of these bodies indicates that more than half of these stars are hosts to multiple planets. This implies that super-Earths may be more likely to form in short-period orbits and in systems with multiple bodies - two characteristics that play important roles in developing models of their formation and dynamical evolution.

Among the currently known super-Earths, a few have gained special attention. CoRoT-7 b, the seventh planet discovered by the CoRoT space telescope (Léger et al. 2009; Queloz et al. 2009; Hatzes et al. 2010, 2011), and GJ 1214 b, the first super-Earth discovered by transit photometry around an M star (Charbonneau et al. 2009), are the first super-Earths for which the values of mass and radius have been measured \([\text{CoRoT-7 b: } 2.38 \ M_\oplus, \ 1.65 \text{ Earth radii } (R_\oplus); \ \text{GJ 1214 b: } 5.69 \ M_\oplus, \ 2.7 \ R_\oplus]\). This major achievement has enabled theoreticians to develop models for the evolution of super-Earths interiors (e.g., Valencia et al. 2006, 2007a,b,c, 2009, 2010; O’Neill & Lenardic 2007; Sotin & Schubert 2009; Tackley & van Heck 2009) and their possible atmospheric properties (e.g., Miller-Ricci et al. 2009; Seager & Deming 2009; Bean et al. 2010; Miller-Ricci & Fortney 2010; Rogers & Seager 2010a,b; Bean et al. 2011; Désert et al. 2011; Heng & Vogt 2011; Berta et al. 2012; Menou 2012; Fraine et al. 2013). The three super-Earth-class bodies GL 581 d (Mayor et al. 2009, Forveille et al. 2011), GL 581

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\(^1\)http://www.eso.org/sci/facilities/lasilla/instruments/harps/

\(^2\)http://www.exoplanets.org/cps.html

\(^3\)http://www.cfa.harvard.edu/MEarth/Welcome.html

\(^4\)http://smsc.cnes.fr/COROT/index.htm

\(^5\)http://kepler.nasa.gov/
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g (Vogt et al. 2010, 2012), and GJ 667C c (Anglada-Escudé et al. 2011) have also made headlines. These planets are the first terrestrial-class objects that have been discovered in their respective habitable zones.

For the past few years, the formation and characteristics of super-Earths have been the subject of extensive research. This is primarily because being slightly larger than a typical terrestrial planet, these objects have the capability of developing moderate atmospheres and may have dynamic interiors with plate tectonics - two conditions that would render a super-Earth potentially habitable if its orbit were in the habitable zone of its host star (see Haghighipour 2011 for a complete review). Also, unlike Earth-sized planets, super-Earths are relatively easy to detect. Current observations of super-Earths have indicated that these objects seem to be more common around cool and low-mass stars (see, e.g., Dressing & Charbonneau 2013, Swift et al. 2013), where the habitable zone is in closer orbit. Two prime examples of such systems are GL 581, an M3V star with one or two potentially habitable super-Earths (Mayor et al. 2009; Vogt et al. 2010, 2012; Forveille et al. 2011), and the M1.5 star GJ 667C, with a 4.5 $M_{\oplus}$ planet in its habitable zone (Anglada-Escudé et al. 2011).

Given the success of observational techniques in detecting potentially habitable super-Earths, and that during the past two years the number of these objects increased twofold, it would be natural to expect that many more habitable super-Earths will be detected in the near future. It is, therefore, imperative to develop a thorough understanding of the formation and dynamical evolution of these bodies, particularly in connection with their habitability. This article presents a review of the current state of research on this topic.

Since there are no super-Earths in the Solar System, it is important to know whether the formation of these objects requires developing new models of planet formation or whether one can use the models of the formation of planets in the Solar System to explain the formation of super-Earths. In the latter case, these models will require major revisions. For instance, one characteristic of super-Earths that presents a challenge to the theories of planet formation is their close-in orbits. While some models suggest that super-Earths were formed at large distances and migrated to their present locations, other models present the possibility of their in-place formation. Fortunately, the physical characteristics of super-Earths, namely their densities, when considered within the context of different planet formation scenarios, present a potential pathway for differentiating between these models. In that respect, the study of super-Earths plays an important role in identifying the most viable planet formation mechanism. The rest of this article presents a review of the current state of research on this topic.

I begin in Section 2 by briefly reviewing the models of planet formation in the Solar System. In Section 3, I discuss in detail the application of these models to the formation of super-Earths, and I conclude in Section 4.

2 MODELS OF PLANET FORMATION

Explaining the formation of planets is one of the most outstanding problems in planetary astronomy. Despite centuries of efforts to explain the formation of the planets of the Solar System, this problem is still unresolved, and planet formation is still an open question. The discovery of extrasolar planets has added even more to these complexities. As explained in Section 1, many of these objects
have physical and orbital properties that are unlike those of the planets in the Solar System and are not well explained by the current models of Solar System formation and dynamics.

Although the diversity of extrasolar planets has been a continuous challenge to the models of planet formation, a common practice in explaining the formation of these objects has been to modify, revise, and/or complement the models of planet formation in the Solar System in such a way that they would be applicable to other planetary bodies. This suggests that to understand the formation of extrasolar planets (such as super-Earths), it is necessary to develop a deep understanding of the models of giant and terrestrial planet formation in the Solar System. This section is devoted to this task. I begin by explaining the growth of dust particles to larger bodies, then discuss different phases of planet growth until a full giant or terrestrial planet is formed.

It is widely accepted that planet formation begins in a circumstellar disk of gas and dust known as a nebula by the growth of dust particles to larger objects. This process, highly dependent on the mass and dynamical properties of the nebula, proceeds in four stages:

- coagulation of dust particles through gentle hitting and sticking, which results in the formation of centimeter- and decimeter-sized objects;
- growth of centimeter- and decimeter-sized bodies to kilometer-sized planetesimals;
- collision and accretion of planetesimals to planetary embryos (moon- to Mars-sized objects) in the inner part of the Solar System and to the cores of giant planets in the outer parts; and
- the accretion of gas and formation of giant planets followed by the collisional growth of planetary embryos to terrestrial-class bodies.

The first stage of this process is well understood. Dust grains at this stage undergo different types of random and systematic motions (Weidenschilling 1977) and frequently collide with one another. Particles smaller than 100 µm are mainly subject to Brownian motion and collide with relative velocities smaller than 1 mm s\(^{-1}\). Larger objects, although slightly faster, are still strongly coupled to the gas, and their dynamics is governed by the gravitational attraction of the central star, non-gravitational forces such as radiation pressure, and their interaction with the nebula through gas drag. Gas molecules, however, are subject to pressure gradient (which is necessary for maintaining the gas at hydrostatic equilibrium), and as a result, their velocities are slightly smaller than Keplerian. The slight velocity differences between dust particles and gas molecules cause dust grains to drift inward and approach one another with small relative velocities (Safronov 1969; Weidenschilling 1980; Nakagawa et al. 1981, 1986; Supulver & Lin 2000; Dullemond & Dominik 2005). Turbulence also causes dust grains to collide and is more effective among same-sized particles. As the collisions of dust particles are gentle, van der Waals forces act between their surfaces and stick the dust particles to one another. As shown by laboratory experiments and computational simulations, such gentle collisions result in the fractal growth of dust grains to larger aggregates (Figure 1) (Smoluchowski 1916; Dominik & Tielens 1997; Blum et al. 1998; Wurm & Blum 1998; Blum & Wurm 2000; Krause & Blum 2004; Blum 2006, 2010; Wada et al. 2007).

While the process of the growth of micrometer-sized dust grains to millimeter-
and centimeter-sized objects is well understood, the growth of the latter bodies to larger sizes (i.e., kilometer size) is still a big mystery. Simulations have shown that as dust particles grow, their coupling to the gas weakens (i.e., their velocities relative to the gas molecules increase), and they show more of their independent dynamics (Weidenschilling 1977). At this stage, differential vertical settling (Safronov 1969), radial drift (Whipple 1972), and turbulence (Völk et al. 1980, Mizuno et al. 1988, Ormel & Cuzzi 2007) play important roles in driving particles relative velocities. The latter causes objects to approach each other rapidly and increases their impact velocities. Results of laboratory experiments and computational simulations have shown that as objects grow to centimeters in size, their sticking efficiency drops dramatically (Blum & Münch 1993), and their relative velocities become so large that their collisions may result in bouncing (bouncing barrier) and/or erosion and fragmentation (fragmentation barrier) (Blum & Wurm 2008, Güttler et al. 2009, Zsom et al. 2010, Beitz et al. 2011).

The above-mentioned bouncing and fragmentation barriers are not the only obstacles in the formation of planetesimals. The sub-Keplerian rotational velocities of gas molecules result in the transfer of angular momentum from solid bodies to the gas and the subsequent drift of these objects toward the central star. The rate of this radial drift is approximately proportional to the size of an object, implying that as an object grows, it approaches the central star in a shorter time. Numerical simulations have indicated that meter-sized bodies have the fastest radial drifts. Combined with turbulence and differential settling, this radial drift increases the relative velocities of solid objects and causes many of them to collide with one another at large speeds. Given that large objects are more prone to collisional destruction (the sticking properties of solid bodies weaken as they grow), it is expected that many of these impacts result in the breakage of the colliding bodies. This process, known as the meter-size barrier, implies that even if the centimeter-size bouncing barrier is overcome, the impact velocities of solid objects become so large that their collisions result in their breaking into small fragments, which subsequently halts their growth to larger sizes. These fragments, even if reaccumulated, will go through the same above-mentioned process and ultimately drift into the central star, leaving the nebula devoid of the solid material necessary for the formation of planetesimals.

Interestingly, despite all these difficulties, planets do exist and so do many kilometer-sized bodies, such as the asteroids and Kuiper belt objects. This implies that during the early stages of planet formation, Nature succeeded in finding a way to overcome the centimeter-sized and meter-sized barriers. It may be that kilometer-sized planetesimals did not form as a result of the mere collisional growth of dust grains; other mechanisms may have also contributed.

A planet-forming nebula is a dynamic environment whose properties and structure vary with time. These variations, in particular in a gaseous disk, may manifest themselves as different structures in the nebula. For instance, regions may appear where the pressure of the gas is locally enhanced. The appearance of such structures will immediately affect the motions of particles in their surroundings. As opposed to a nebula with a monotonic radial pressure profile where gas drag and pressure gradient cause inward migration of solids, in the vicinity of pressure-enhanced regions, the velocity differences between solid objects and gas molecules cause solid particles to undergo inward and outward migrations and to accumulate around the locations of pressure maxima (Haghighipour & Boss 2003a,b; Haghighipour 2005).
In a gaseous disk, the turbulent eddies created by magnetorotational instability are examples of such high-pressure regions. As Johansen et al. (2006, 2007, 2008) have shown, the formation of these turbulent eddies causes small centimeter- and decimeter-sized objects to accumulate in their vicinities and increases the local density of solid material. As the accumulation of solid objects continues, their local spatial density increases until their region becomes gravitationally unstable and the accumulated bodies fragment into several 100–1,000-km-sized planetesimals. This mechanism, known as streaming instability, has been presented as a scenario for planetesimal formation. [See Chiang & Youdin (2010) for a review and Cuzzi et al. (2008) and Weidenschilling (2010) for alternative viewpoints.]

It is important to note that as shown by Shariff & Cuzzi (2011), the local enhancement of solid to gas surface density necessary for the onset of instability is achievable only when the turbulence is extremely weak. These authors indicate that when the effect of turbulent mass diffusivity is taken into account, streaming instability becomes inefficient, and the growth rate of planetesimals reduces significantly.

Other mechanisms of the formation of planetesimals include trapping dust particles in vortices (Barge & Sommeria 1995, Klahr & Henning 1997, Lyra et al. 2009a), trapping particles in pressure enhanced regions created by the evaporation front of water in the protoplanetary disk (Kretke & Lin 2007; Brauer et al. 2008a,b; Lyra et al. 2009b), turbulent concentration of solids (Chambers 2010), turbulent clustering of protoplanetary bodies (Pan et al. 2011), concentration of solid objects at the snowline (the region beyond which water is in the permanent state of ice) as a result of the sublimation of drifting ice aggregates (Aumatell & Wurm 2011), trapping of solid objects in dead zones (Gressel et al. 2012) and at the boundary between steady super/sub-Keplerian flow created by inhomogeneous growth of magnetorotational instabilities (Kato et al. 2012), rapid coagulation of porous dust aggregates outside the snowline (Okuzumi et al. 2012), and planetesimal formation in self-gravitating disks (Gibbons et al. 2012, Shi & Chiang 2013).

The four stages of planet formation outlined above share one interesting feature: The underlying physics of each stage is almost distinct from that of the other phases. This makes it possible to study each phase separately. Once the dust grains have grown and kilometer-sized planetesimals are formed, although the circumstellar disk still contains gas and dust, its dynamics is now mainly driven by the interaction of planetesimals with one another. These interactions are primarily gravitational, although gas drag also plays a role. At this stage, because the planetesimals are the main components populating the disk, collisions among these objects are frequent, which results in low eccentricities and low inclinations for these bodies. Because the relative velocity between two bodies is an increasing function of their orbital eccentricities, lowering the eccentricity of planetesimals due to their mutual collisions and dynamical friction, combined with their almost coplanar orbits, reduces their relative velocities. The latter facilitates the merging of these objects and enhances the rate of their accretion to larger bodies.

As a planetesimal grows, the influence zone of its gravitational field expands and as a result, it attracts more material from its surroundings. In other words, more material will be available for the planetesimal to accrete, and the rate of its growth increases. Known as runaway growth, this process results in the growth of kilometer-sized planetesimals to larger bodies in a short time (Safronov 1969; Greenberg et al. 1978; Wetherill & Stewart 1989, 1993; Ida & Makino 1993;
Runaway growth is a local process. Since the collision of two objects is more likely to result in their coalescence when their relative velocity is small, the effectiveness of this process in producing larger bodies, and the type and size of the resulting objects, varies at different distances from the central star. At large distances (e.g., > 5 AU from the Sun), where the rotational velocities are small, planetesimals approach each other with small relative velocities, and their impacts are likely to result in accretion. Also, because the temperature in the circumstellar disk is low at such distances, the bulk material of such planetesimals is primarily ice, which increases the efficiency of their sticking at the time of their collision. As a result, planetesimals at large distances grow to objects of a few Earth masses in a short time. As this process occurs while the nebular gas is still present, a growing object gradually attracts gas from its surroundings, forming a large body with a thick gaseous envelope and a mass equal to a few hundred Earth masses. At this state, a gas-giant planet is formed. This scenario, known as the core-accretion model, has been proposed as a mechanism for the formation of gas-giant planets in the Solar System (Pollack et al. 1996, Hubickyj et al. 2005, Lissauer et al. 2009, Movshovitz et al. 2010).

As the giant planets form at large orbits, the runaway accretion takes a slightly different path in the inner parts of the disk. Similar to the formation of the cores of gas-giant planets, the collisions of planetesimals at this stage may result in their growth to larger bodies. However, because the orbital motions of planetesimals are faster, they may approach each other with larger relative velocities. Also, many of these objects may lose their surface ices and other volatiles at closer distances, and as a result, when they collide with one another, the efficiency of their accretion will not be as high as for those at larger orbits. Simulations of the collision and growth of planetesimals in the inner part of the Solar System have shown that instead of forming objects as big as the cores of giant planets, accretion of these bodies results in the formation of several hundred moon- to Mars-sized objects known as planetary embryos. Computational simulations (Bromley & Kenyon 2006) and analytical analysis (Goldreich et al. 2004) have shown that when the masses of these embryos reach lunar mass, the dynamical friction of the swarm of planetesimals can no longer dampen their orbits, and their runaway growth ends. At this stage, the gravitational perturbation of the resulting planetary embryos, combined with the perturbation of giant planets, strongly affects the dynamics of smaller planetesimals and causes many of them to collide at high velocities and shatter one another, and/or their orbits become highly eccentric, and they subsequently scatter to large distances where they may leave the gravitational field of the system. This growth and clearing process continues until terrestrial planets are formed and the smaller remaining bodies (asteroids) are in stable orbits (Figure 2) (Wetherill 1990a,b, 1994, 1996; Kokubo & Ida 1995, 1998, 2007; Chambers & Wetherill 1998, 2001; Agnor et al. 1999; Morbidelli et al. 2000, 2012; Chambers 2001; Chambers & Cassen 2002; Levison & Agnor 2003; Raymond et al. 2004, 2005a,b, 2006b, 2007, 2009; Kokubo et al. 2006; O'Brien et al. 2006; Hansen 2009; Schlichting et al. 2012; Torres et al. 2013; Haghighipour et al. submitted; Izidoro et al. submitted). Since the accretion and reaccretion of bodies in smaller orbits are not as efficient as in the outer regions, unlike the growth of gas-giant planets, the formation of terrestrial bodies will take several hundred million years. Figure 2 shows the time evolution of a sample simulation of terrestrial planet formation (Haghighipour et al.
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submitted; Izidoro et al. submitted). The planet formation models as explained above, although capable of explaining many features of the Solar System, face several complicated challenges. The core-accretion model, for instance, requires the nebular gas to be available for $\sim 10$ Ma while the core of Jupiter grows and accretes gas from its surroundings (Pollack et al. 1996). However, the observational estimates of the lifetimes of disks around young stars suggest a lifetime of 0.1-10 Ma, with 3 Ma being the age at which half the stars show evidence of disks (Strom et al. 1993, Haisch et al. 2001, Chen & Kamp 2004, Maercker et al. 2006). These simulations also suggest a solid core for Jupiter with a mass of $\sim 10M_\oplus$. Computational modeling of the interiors of Jupiter and Saturn, however, has indicated different possible values for the cores of these objects, ranging from 0 to as large as $14M_\oplus$ (Guillot 2005, Militzer et al. 2008). It is unclear what the actual masses of the cores of our gas-giant planets are, and if smaller than $10M_\oplus$, how they accumulated their thick envelopes in a short time. I refer the reader to a review by Guillot (2005) for more details.

To overcome these difficulties, the core-accretion model has undergone several improvements. Hubickyj et al. (2005) and Lissauer et al. (2009) have shown that increasing the surface density of the nebula to higher than that suggested by Pollack et al. (1996) significantly reduces the time of the giant planet formation. An improved treatment of grain physics as given by Podolak (2003), Movshovitz & Podolak (2008), and Movshovitz et al. (2010) has also indicated that the value of the grain opacity in the envelope of the growing Jupiter in the original core-accretion model (Pollack et al. 1996) is too high, and a lower value has to be adopted. This lower opacity has led to a revised version of the core-accretion model in which the time of giant planet formation is considerably smaller (Hubickyj et al. 2005, Movshovitz et al. 2010). Most recently, Bromley & Kenyon (2011) have developed a new hybrid N-body-coagulation code that has enabled the authors to form Saturn- and Jupiter-sized planets in $\sim 1$ Ma.

An alternative model for the formation of gas-giant planets addresses this issue by proposing rapid formation of giant planets in a gravitationally unstable nebula (Boss 2000a,b, 2003; Mayer et al. 2002, 2004, 2007; Durisen et al. 2007; Boley 2009; Boley et al. 2010; Cai et al. 2010). Known as the disk-instability scenario, this model suggests that local gravitational instabilities in the solar nebula may result in the fragmentation of the disk to massive clumps that subsequently contract and form gas-giant planets in a short time. Boss’s (2000a,b) and Mayer et al.’s (2002, 2003, 2004) results show that an unstable disk can break up into giant gaseous protoplanets in as short a time as $\sim 1,000$ years. Although this mechanism presents a fast track to the formation of a gas-giant planet, it suffers from the lack of an efficient cooling process necessary to take energy away from a planet-forming clump in a sufficiently short time before it disperses.

3 FORMATION OF SUPER-EARTHS

The extent to which current planet formation scenarios can be used to explain the formation of super-Earths varies with the mass and orbital architecture of these objects. Since the dynamics and characteristics of planet-forming nebulae are different for stars with different spectral types, the parent stars of super-Earths also play an important role. The range of masses for the currently known super-Earths, when considered within the context of giant and terrestrial planet
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formation scenarios, points to two general pathways for the formation of these objects. The low-mass super-Earths could have formed in place following a similar process as the formation of terrestrial planets in the Solar System (see, e.g., Chiang & Laughlin 2012). The larger super-Earths, with masses close to their upper limit, may be the result of an unsuccessful and incomplete giant planet formation (see, e.g., Rogers et al. 2011). In this scenario, the super-Earths larger than terrestrial masses, combined with the fact that many of these objects are in short-period orbits, point to a formation scenario in which super-Earths are formed at large distances (where more material is available for their growth) and either migrate to their current locations as they interact with the protoplanetary disk (Kennedy & Kenyon 2008b) or are scattered to their current orbits as a result of interactions with other cores and/or planets (Terquem & Papaloizou 2007). In other words, the formation of these objects may have occurred while their orbital elements were evolving (Terquem & Papaloizou 2007; Kennedy & Kenyon 2008a,b). This mechanism naturally favors the core-accretion model of gas-giant planet formation, although attempts have also been made to explain the formation of super-Earths via the disk-instability scenario (see Section 3.3).

As mentioned above, super-Earths owe their popularity to their masses and sizes, which under favorable conditions may render them habitable. While planet formation models allow for the formation of super-Earths around all types of stars (either as a failed core of a giant planet or as a slightly larger terrestrial-class object), because of the current sensitivity of detection techniques, a great deal of interest exists in super-Earths in the habitable zones of cool and low-mass stars (e.g., M dwarfs). For this reason, I devote the rest of this article to presenting a review of the models of super-Earth formation around M stars.

3.1 Formation of Super-Earths Around Low-Mass Stars

The discovery of planets of different sizes, from Jovian-type [e.g., GJ 876 b, c, and e (Rivera et al. 2010); HIP 57050 b (Haghighipour et al. 2010); GL 581 b (Bonfils et al. 2005); KOI-254 b (Johnson et al. 2012); Kepler-32 d (Swift et al. 2013)] to small super-Earths [e.g., GL 581 c, d, e, and g (Udry et al. 2007, Mayor et al. 2009, Vogt et al. 2010); JG 667C c (Anglada-Escudé et al. 2011); Kepler-32 b and c (Swift et al. 2013)] around M dwarfs indicates that both giant and terrestrial planet formation can proceed efficiently around low-mass stars. This implies that the circumstellar disks around these stars can accommodate the formation of super-Earths both as a failed core of a giant planet through the gas-giant planet formation process, and also as small terrestrial-class objects through direct collisional growth of protoplanetary bodies and planetary embryos. These mechanisms have to also account for the short periods of super-Earths, whether through planet migration, planet-planet scattering, or a combination of both. I begin this section by considering the core-accretion model as the mechanism for the formation of super-Earths. As mentioned above, the discovery of super-Earths can be taken as strong evidence in support of this model. However, as is explained at the end of the next section, this mechanism alone cannot explain the formation and orbital architecture of all the currently known super-Earths. Other effects such as the evolution of the central star and planet migration have to be taken into consideration as well. I discuss these effects in the next section and conclude this article by reviewing the formation of super-Earths through the disk-instability model.
3.2 The Core-Accretion Model

As mentioned in Section 2, the efficiency of the core-accretion model and the rate of the growth of the cores of giant planets increase with the disk surface density. Around low-mass stars, where the surface density of the disk is smaller than around the Sun, the solid material (i.e., the planetesimals) is more spatially scattered, and as a result, the collisions among planetesimals and planetary embryos are less frequent. This smaller rate of collision prolongs the growth of planetesimals to larger sizes, and causes the time of the core growth around low-mass stars to be several times longer than the time of the formation of Jupiter around the Sun. As shown by Laughlin et al. (2004), in disks around stars with masses smaller than 0.5 solar masses ($M_{\odot}$), the core-accretion mechanism can produce planets ranging from terrestrial-class to Neptune sizes. However, the time for the formation of these objects is much longer than the time for the formation of Jupiter in the Solar System through the core-accretion model. During this time, around M stars, for instance, the gaseous component of the circumstellar disk disperses, leaving the slowly growing core with much less gas to accrete.

The short lifetime of the gas in circumstellar disks around M stars can be attributed to two important factors:

- the high internal radiation of young M stars (at this stage, these stars are almost as bright as Sun-like stars), and
- external perturbations from other close-by stars.

The latter is primarily due to the fact that most stars are formed in clusters (Lada & Lada 2003), and as such, their circumstellar disks are strongly affected by the gravitational perturbations and the radiations of other stars (Adams et al. 2004). For M stars, this causes the circumstellar disk to receive a high amount of radiation from both the central star and external sources. This high amount of radiation combined with the low masses of M stars, which points to their small gravitational fields, increases the effectiveness of the photoevaporation of the gaseous component of the circumstellar disk by up to two orders of magnitude. As a result, the majority of the gas leaves the disk at the early stages of giant planet formation, leaving a still-forming core with not much gas to accrete.

3.2.1 Effect of stellar evolution

Although the growth of giant planets cores through collision and accretion of planetesimals is similar in disks around solar-type and low-mass stars, the fact that around smaller stars this process takes longer introduces a fundamental difference in the formation of giant planets in these two environments. As opposed to young Sun-like stars whose luminosities stay almost constant during the formation of giant and terrestrial planets (e.g., 10-100 Ma), the luminosity of a premain sequence, low-mass star (e.g., 0.5$M_{\odot}$) fades by a factor of 10 to 100 during this process (Hayashi 1981). This causes the internal temperature of the circumstellar disk to decrease, which subsequently causes the disks snowline to move toward the central star and to close distances. The forward migration of the snowline results in an increase in the population of icy materials (kilometer-sized and larger planetesimals) in the outer regions of the disk, which in turn increases the efficiency of the collisional growth of these objects to protoplanetary bodies (as mentioned in Section 2, sticking is more efficient among icy bodies). As shown by Kennedy et al. (2006), around a 0.25-$M_{\odot}$ star, the moving snowline
causes rapid formation of planetary embryos within a few million years (also see Kennedy et al. 2007). Subsequent collisions and interactions among these objects result in the formation of super-Earths in approximately 50-500 Ma.

3.2.2 Effect of planet migration

As mentioned above, one of the major developments in the field of planetary dynamics that was a direct consequence of the detection of extrasolar planets is the concept of planet migration. Although previously post-formation migration had been proposed as a mechanism to explain the orbital architecture of small bodies in the Solar System (e.g., moons of giant planets and Kuiper belt objects), the migration of planets during their formation had not been incorporated into the models of planetary formation. In other words, the planet formation scenarios mentioned above were developed assuming that planets form in place. The discovery of extrasolar planets, almost from the beginning, challenged this assumption. The detection of the first hot Jupiter in a 4-day orbit around the star 51 Pegasi (Mayor & Queloz 1995) revealed that planet migration is an inseparable part of the evolution of a planetary system and prompted astronomers to revisit this concept and to incorporate it into their models of planet formation. Today, planet migration is well developed and widely accepted as part of a comprehensive planet formation scenario.

Planetary and satellite migration has long been recognized as a major contributor to the formation and orbital architecture of planets, their moons, and other minor bodies in the Solar System. As shown by Greenberg et al. (1972) and Greenberg (1973), mean-motion resonances (i.e., commensurable orbital periods) among the natural satellites of giant planets (e.g., Titan and Hyperion, satellites of Saturn) may have been the result of the radial migration of these objects due to their tidal interactions with their parent planets (Goldreich 1965). The dynamical architecture of Galilean satellites, with their three-body, Laplace resonance, has also been attributed to the migration of these objects. It is accepted that these satellites migrated inward during their formation as a result of interacting with the circumplanetary disk of satellites around Jupiter (Canup & Ward 2002), and subsequently by tidal forces after their formation (Peale & Lee 2002). The lack of irregular satellites between Callisto, the outermost Galilean satellite, and Themisto, the innermost irregular satellite of Jupiter, also can be explained by a dynamical clearing process that occurred during the formation and migration of Galilean satellites (Haghighipour & Jewitt 2008).

Among the planets of our Solar System, the post-formation, planetesimal-driven migration of giant planets has been proposed as a mechanism to explain the current state of the asteroid belt (Tsiganis et al. 2005; Minton & Malhotra 2009, 2011; see also Gomes 1997), late heavy bombardment (Gomes et al. 2005), the origin of Jupiter Trojan asteroids (Morbidelli et al. 2005), the effects of secular resonances on terrestrial planet formation (Agnor & Lin 2012), and the small mass and size of Mars (Walsh et al. 2011). I refer the reader to Morbidelli et al. (2012) for a review on these topics.

The idea of the migration of planetary bodies was first proposed by Fernandez...
These authors suggested that after the dispersal of the nebular gas, fully formed giant planets may drift from their original orbits due to the exchange of angular momentum with the disk of planetesimals. As a result of this post-formation migration, small bodies either are scattered out of the Solar System or may reach other regions where they may reside in long-term stable orbits. As shown by Malhotra (1993, 1995), this mechanism can explain the peculiar orbit of Pluto (highly eccentric, inclined, and long-term chaotic), and as shown by Malhotra (1996) and Hahn & Malhotra (2005), it can also explain the dynamical structure of Kuiper belt objects.

The past two decades have witnessed major developments in the theories of planet migration. Simulations of the formation of planetary bodies and their interactions with circumstellar disks have shown that planet migration does not have to occur necessarily after the planets are fully formed. In fact, planets can migrate while they are forming as a result of exchanging angular momentum with their surrounding environment. This naturally suggests that the physical and dynamical characteristics of a planet and its circumstellar disk will play an important role in this process. For instance, the planet may undergo type I migration, in which case it does not accrete nebular material as it migrates (Figure 3a). Conversely, the planet may be large and accrete nebular material, in which case it may create a gap in the disk as it migrates (Figure 3b). This type of migration is known as type II migration. Planet migration may occur in other forms as well.

The contribution of planet migration to the formation of close-in super-Earths may appear in different forms. The most common scenario involves the inward migration of a fully formed giant planet in a disk of planetesimals and planetary embryos. The giant planet in this scenario affects the dynamics of protoplanetary bodies interior to its orbit by either increasing their orbital eccentricities and scattering them to larger distances or causing them to migrate to closer orbits. The migrating protoplanets may be shepherded by the giant planet into small close-in regions, where they are captured in mean-motion resonances. As Zhou et al. (2005), Fogg & Nelson (2005, 2006, 2007a,b, 2009), and Raymond et al. (2008) have shown, around Sun-like stars, the shepherded protoplanets may also collide and grow to terrestrial-class and super-Earth objects (see, e.g., Figure 6b). Studies of the back-scattered objects in the simulations of disks around massive stars have shown that these bodies may also collide and grow to planetary sizes (Mandell & Sigurdsson 2003, Raymond et al. 2006a, Mandell et al. 2007).

While around Sun-like stars, despite the out-scattering of protoplanetary bodies during the migration of a giant planet, the formation of super-Earths through the collision and growth of planetesimals and planetary embryos proceeds efficiently, around low-mass stars this scenario is not always the case. Simulations of the dynamics of protoplanetary bodies at distances smaller than 0.2 AU around a 0.3 $M_\odot$ star have shown that during the inward migration of one or several giant planets (the latter involves migrating planets in mean-motion resonances), the majority of the protoplanets leave the system and do not contribute to the forma-

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I do not discuss these mechanisms here, as they may not be entirely relevant to the formation and dynamical evolution of super-Earths. Instead, I refer the reader to numerous articles that have been published on these subjects. Unfortunately, the richness of the literature does not allow me to cite all these articles here, but among them, one can refer to Nelson et al. (2001), Masset & Snellgrove (2001), Papaloizou & Terquem (2006), Chambers (2009), Armitage (2010), and a recent review by Baruteau & Masset (2013).
tion of close-in Earth-sized bodies and/or super-Earths (Figure 4) (Haghighipour & Rastegar 2011). These results suggest that the currently known small planets around M stars might have formed at larger distances and were either scattered to their current close-in orbits (e.g., GJ 876 d; see Figure 5) or migrated into their orbits while captured in a mean-motion resonance with a migrating planet.

The above-mentioned scenario for the formation of close-in super-Earths is based on the fact that giant planets are formed long before the protoplanetary bodies grow to larger sizes. The underlying assumption in this scenario is that the giant planet does not migrate during its formation, and the migration of the planetary embryos (the moon- to Mars-sized objects) is also ignored. However, not only do the cores of still-forming giant planets migrate (Alibert et al. 2004), so too do the planetary embryos. While migrating, the embryos may undergo orbital crossing and collisional merging, which may result in their growth to a few super-Earths, especially in mean motion resonances. Simulating the interactions of 25 protoplanetary objects with masses ranging from 0.1 to 1 \( M_\oplus \), Terquem & Papaloizou (2007) have shown that a few close-in super-Earths may form in this way with masses up to 12\( M_\oplus \). The results of these simulations suggest that in systems in which merging of migrating cores results in the formation of super-Earths and Neptune-like planets, such planets will always be accompanied by giant bodies and most likely will be in mean-motion resonances. Similar results have also been reported by Haghighipour & Rastegar (2011).

Interestingly, several planetary systems have been discovered in which central stars host only small Neptune-sized objects and super-Earths (e.g., HD 69830, GL 581). The planets in these systems do not have a Jupiter-like companion that could have migrated to facilitate their formation. Such systems seem to imply that a different mechanism may be responsible for the formation of their super-Earth bodies. Kennedy & Kenyon (2008a) and Kenyon & Bromley (2009) have suggested that the migration of protoplanetary embryos may be the key in facilitating the close-in accretion of these objects. These authors considered a circumstellar disk with a density enhancement at the region of its snowline and simulated the dynamics and growth of its planetary embryos. They showed that while interacting with one another (colliding and accreting), many of these objects may migrate toward the central star. Around a solar-type star, the time of such migrations for an Earth-sized planet at 1 AU is \( \sim 10^5 - 10^6 \) years - much smaller than the time for the chaotic growth of a typical moon- or Mars-sized embryo (10\(^8\) years) (Goldreich et al. 2004). This implies that most of the migration occurs prior to the onset of the final growth. Depending on their relative velocities, the interactions among the migrating embryos may result in their growth, scattering, and/or shepherding, as in the case of a migrating giant planet. Simulations by Kennedy & Kenyon (2008b) and Kenyon & Bromley (2009) have shown that super-Earth objects with masses up to 8 \( M_\oplus \) may form in this way around stars ranging from 0.25 to 2 \( M_\odot \) (Figure 6).

### 3.3 The Disk-Instability Model

The formation of super-Earths through the mechanisms explained above, particularly when those mechanisms are used to explain the formation of these objects at the higher end of their mass range, naturally favors the core-accretion model of giant planet formation. However, the fact that Jovian-type planets have been discovered around low-mass stars (e.g., GJ 876, with three planets ranging from
1 Uranus mass to 2.2 Jupiter masses in \(~\sim 120-, 60-,\) and 30-day orbits; HIP57050, with a Saturn-mass planet in a \(~\sim 40\)-day orbit) suggests that the disk-instability model may also be able to form close-in super-Earths, especially those that are considered as failed cores of giant planets. As explained above, given the low masses of the circumstellar disks around M stars, the existence of giant planets around these stars suggests that they might have formed at large distances and migrated to their current orbits. This is because in a planet-forming nebula, more nebular material is available at outer regions that can then facilitate the formation of a giant planet through the core-accretion model. The availability of more mass at outer distances in a disk may also trigger the formation of giant planets around M stars through the disk-instability scenario. Recall that in this scenario, clumps, formed in an unstable gaseous disk, collapse and form gas-giant planets (e.g., Boss 2000b, Mayer et al. 2002). After the giant planets are formed, a secondary process is needed to remove their gaseous envelopes. As Boss (2006) has shown, such collapsing clumps can form around a 0.5 $M_\odot$ star at a distance of \(~\sim 8\) AU (Figure 7). This author suggests that, as most stars are formed in clusters and in high-mass, star-forming regions, intense far/extreme UV radiations from nearby O stars may rapidly (within 1 Ma) photoevaporate the gaseous envelopes around giant planets, leaving them with large super-Earth cores. Similar mechanisms have been suggested for the formation of Uranus and Neptune in the Solar System (Boss et al. 2002). A subsequent migration, similar to that suggested by Michael et al. (2011), may then move these cores to close-in orbits.

4 CONCLUDING REMARKS

As evident from this review, it is generally accepted that super-Earths are formed through a combination of a core accumulation process and planetary migration. Modeling the formation of these objects requires the simulation of the collisional growth of planetary embryos and their subsequent interactions with the protoplanetary disk. A realistic model requires global treatment of the disk and inclusion of large numbers of planetesimals and planetary embryos. In practice, such simulations are computationally expensive. To avoid such complications, most of the current models of super-Earth formation include only small numbers of objects (e.g., cores, progenitors, protoplanets, planetesimals). As shown by McNeil & Nelson (2010), in systems with large numbers of bodies (e.g., several thousand planetesimals and larger objects), the combination of traditional core accretion and type I planet migration may not produce objects larger than 3-4 $M_\oplus$ in close-in (e.g., \(~\leq 0.5\) AU) orbits. Although the systems studied carry some simplifying assumption, McNeil & Nelson's results point to an interesting conclusion: While the combination of core accretion and planet migration seems to be a viable mechanism for the formation of close-in super-Earths, the formation of these objects is still an open question, and a comprehensive theory for their formation requires more sophisticated computational modeling, with possibly entirely new physics, as yet to be discovered.

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Table 1: Currently known extrasolar planets with masses up to 10 Earth-masses. The quantities $M, P, a$ and $e$ represent the mass (in terms of Earth’s mass $M_\oplus$), orbital period, semimajor axis, and orbital eccentricity of the planet. The mass of the central star is shown by $M_*$ and is given in the units of solar-masses ($M_\odot$).

| Planet                  | $M (M_\oplus)$ | $P$ (day)   | $a$ (AU)  | $e$  | Stellar Type | $M_*(M_\odot)$ |
|-------------------------|----------------|-------------|-----------|------|--------------|-----------------|
| KOI-55 c                | 0.6678         | 0.34289     | 0.0076    | -    | sdB          |                 |
| Kepler-42 d             | 0.954          | 1.856169    | 0.0154    | -    |              | 0.13            |
| Kepler-42 c             | 1.908          | 0.45328509  | 0.006     | -    |              | 0.13            |
| Gl 581 e                | 1.9398         | 3.14945     | 0.028     | 0.32 | M2.5V        |                 |
| Kepler-11 f             | 2.301366       | 46.68876    | 0.25      | 0.95 | G            |                 |
| HD 20794 c              | 2.4168         | 40.114      | 0.2036    | 0    | G8V          |                 |
| HD 20794 b              | 2.703          | 18.315      | 0.1207    | 0    | G8V          |                 |
| HD 215152 b             | 2.7666         | 7.2825      | 0.0652    | 0.34 | -            | K0              |
| Kepler-42 b             | 2.862          | 1.2137672   | 0.0116    | -    |              | 0.13            |
| HD 215152 c             | 3.0846         | 10.866      | 0.0852    | 0.38 | -            | K0              |
| Kepler-20 e             | 3.0846         | 6.098493    | 0.0507    | 0.912| G8           |                 |
| MOA-2007-BLG -192-L b   | 3.18           | -           | 0.66      | -    | M            | 0.06            |
| Kepler-32 b             | 3.4            | 5.90        | 0.0519    | -    | M1V          | 0.54            |
| HD 85512 b              | 3.498          | 58.43       | 0.26      | 0.11 | K5V          | 0.69            |
| HD 39194 b              | 3.7206         | 5.6363      | 0.0519    | 0.2  | K0V          |                 |
| Kepler-32 c             | 3.8            | 8.75        | 0.067     | -    | M1V          | 0.54            |
| PSR 1257 +12 d          | 3.816          | 98.2114     | 0.46      | 0.025| -            |                 |
| PSR 1257 +12 c          | 4.134          | 66.5419     | 0.36      | 0.018| -            |                 |
| HD 156668 b             | 4.1658         | 4.646       | 0.05      | 0    | K3V          | 0.772           |
| HD 40307 b              | 4.1976         | 4.3115      | 0.047     | 0    | K2.5V        | 0.77            |
| GJ 667C c               | 4.2612         | 28.13       | 0.1251    | 0.34 | M1.5V        | 0.33            |
| Kepler-11 b             | 4.30254        | 10.30375    | 0.091     | 0    | G            | 0.95            |
| KOI-55 b                | 4.452          | 0.2401      | 0.006     | -    |              | 0.496           |
| Kepler-10 b             | 4.5474         | 0.837495    | 0.01684   | 0    | G            | 0.895           |
| HD 20794 d              | 4.77           | 90.309      | 0.3499    | 0    | G8V          | 0.7             |
| CoRoT-7 b               | 4.8018         | 0.853585    | 0.0172    | 0    | K0V          | 0.93            |
| 61 Vir b                | 5.088          | 4.215       | 0.050201  | 0.12 | G5V          | 0.95            |
| HD 39194 d              | 5.1516         | 33.941      | 0.172     | 0.2  | K0V          |                 |
| HD 136352 b             | 5.2788         | 11.577      | 0.0933    | 0.18 | G4V          |                 |
| Gl 581 c                | 5.406          | 12.9182     | 0.073     | 0.07 | M2.5V        | 0.31            |
Table 2: Continuing from Table 1. Currently known extrasolar planets with masses up to 10 Earth-masses. The quantities $M, P, a$ and $e$ represent the mass (in terms of Earth’s mass $M_\oplus$), orbital period, semimajor axis, and orbital eccentricity of the planet. The mass of the central star is shown by $M_\star$ and is given in the units of solar-masses ($M_\odot$).

| Planet             | $M(M_\oplus)$ | $P$ (day) | $a$ (AU) | $e$   | Stellar Type | $M_\star(M_\odot)$ |
|--------------------|---------------|-----------|----------|-------|--------------|-------------------|
| OGLE-2005-390L b   | 5.406         | 3500      | 2.1      | -     | 0.22         | M                 |
| GJ 667C b          | 5.46324       | 7.199     | 0.0504   | 0.09  | 0.33         | M1.5V             |
| GJ 433 b           | 5.7876        | 7.3709    | 0.058    | 0.08  | 0.48         | M1.5              |
| HD 1461 c          | 5.9148        | 13.505    | 0.1117   | 0     | 1.08         | G0V               |
| HD 39194 c         | 5.9466        | 14.025    | 0.0954   | 0.11  | -            | K0V               |
| Gl 581 d           | 6.042         | 66.64     | 0.22     | 0.25  | 0.31         | M2.5V             |
| Kepler-11 d        | 6.10242       | 22.68719  | 0.159    | 0     | 0.95         | G                 |
| HD 154088 b        | 6.1374        | 18.596    | 0.1316   | 0.38  | -            | K0IV              |
| GJ 1214 b          | 6.36          | 1.58040482| 0.014    | 0.27  | 0.153        | M                 |
| HD 215497 b        | 6.36          | 3.93404   | 0.047    | 0.16  | 0.87         | K3V               |
| HD 97658 b         | 6.36          | 9.4957    | 0.0797   | 0.13  | 0.85         | K1V               |
| Gl 876 d           | 6.678         | 1.93778   | 0.0208   | 0.21  | 0.334        | M4 V              |
| HD 40307 c         | 6.8688        | 9.62      | 0.081    | 0     | 0.77         | K2.5V             |
| Kepler-18 b        | 6.9006        | 3.504725  | 0.0447   | -     | 0.972        | -                 |
| GJ 3634 b          | 6.996         | 2.64561   | 0.0287   | 0.08  | 0.45         | M2.5              |
| Kepler-9 d         | 6.996         | 1.592851  | 0.0273   | -     | 1            | -                 |
| HD 181433 b        | 7.5684        | 9.3743    | 0.08     | 0.39  | 0.78         | K3IV              |
| HD 1461 b          | 7.6002        | 5.7727    | 0.063    | 0.14  | 1.08         | G0V               |
| HD 93385 b         | 8.3634        | 13.186    | 0.1116   | 0.15  | -            | G2V               |
| CoRoT-7 c          | 8.3952        | 3.698     | 0.046    | 0     | 0.93         | K0V               |
| Kepler-11 e        | 8.40474       | 31.9959   | 0.194    | 0     | 0.95         | G                 |
| GJ 176 b           | 8.427         | 8.7836    | 0.066    | 0     | 0.49         | M2.5V             |
| 55 Cnc e           | 8.586         | 0.7365449 | 0.0156   | 0.06  | 0.905        | K0IV-V            |
| Kepler-20 b        | 8.586         | 3.6961219 | 0.0453   | 0.32  | 0.912        | G8                |
| HD 96700 b         | 9.0312        | 8.1256    | 0.0774   | 0.1   | -            | G0V               |
| HD 40307 d         | 9.1584        | 20.46     | 0.134    | 0     | 0.77         | K2.5V             |
| HD 7924 b          | 9.222         | 5.3978    | 0.057    | 0.17  | 0.832        | K0V               |
| HD 134606 b        | 9.2856        | 12.083    | 0.102    | 0.15  | -            | G6IV              |
| HD 136352 d        | 9.54          | 106.72    | 0.411    | 0.43  | -            | G4V               |
| HD 189567 b        | 10.0488       | -         | 14.275   | 0.11  | 0.23         | G2V               |
| HD 93385 c         | 10.1124       | -         | 46.025   | 0.21  | 0.24         | G2V               |
Figure 1: Coagulation of dust particles to fractal aggregates. Figure courtesy of J. Blum.
Figure 2: Snapshots of the accretion of planetesimals and planetary embryos to terrestrial-size planets. The disk has a radial surface density profile of $-1.5$ with its value at 1 AU equal to 8 g cm$^{-3}$. Mean-motion and secular resonances with Jupiter and Saturn are also shown. Figure courtesy of A. Izidoro.
Figure 3: Type I (top) and type II (bottom) planetary migration. Figures courtesy of F. Massé.
Figure 4: Accretion of protoplanetary bodies during the migration of a giant planet around a $0.3M_\odot$ M star (Haghighipour & Rastegar 2011).
Figure 5: Accretion of protoplanetary bodies during the migration of two giant planets around a $0.3M_\odot$ M star. As shown here, the system becomes stable with two giant planets in a 1:2 MMR and a super-Earth in a short-period orbit (e.g., GJ 876).
Figure 6: Migration and accretion of planetary embryos and the formation of super-Earths. Top: The formation of an icy $3M_\oplus$ object at 0.5 AU. The super-Earth has two giant companions, one at 10 AU (not shown here) and one at 4 AU with a mass of $1,200 M_\oplus$. Figure courtesy of S. Kenyon. Bottom: A combination of the migration and accretion of embryos to super-Earth bodies and their capture in MMR resonances. Figure courtesy of J.-L. Zhou.
Figure 7: A snapshot of a simulation of the formation of super-Earths around a 0.5 \( M_\odot \) star in the disk-instability model. The four clumps shown in light blue are potential mini-Neptune and super-Earth objects. Figure courtesy of A. Boss.