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Challenges in planet formation

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Abstract Over the past two decades, large strides have been made in the field of planet formation. Yet fundamental questions remain. Here we review our state of understanding of five fundamental bottlenecks in planet formation. These are the following: (1) the structure and evolution of protoplanetary disks; (2) the growth of the first planetesimals; (3) orbital migration driven by interactions between protoplanets and gaseous disk; (4) the origin of the Solar System's orbital architecture; and (5) the relationship between observed super-Earths and our own terrestrial planets. Given our lack of understanding of these issues, even the most successful formation models remain on shaky ground.

1. Introduction

The origin of planets is a vast, complex, and still quite mysterious subject. Despite decades of space exploration, ground-based observations, and detailed analyses of meteorites and cometary grains (the only space samples available in our laboratories), it is still not clear how the planets of the solar system formed. The discovery of extrasolar planets has added confusion to the problem, bringing to light evidence that planetary systems are very diverse, that our solar system is not a typical case and that categories of planets that do not exist in our system are common elsewhere (e.g., the super-Earth planets).

There are several recent reviews on planet formation. *Johansen et al.* [2014] focused on planetesimal formation, *Morbidelli et al.* [2012] and *Raymond et al.* [2014] focused on terrestrial planets, and *Helled et al.* [2014] focused on giant planets. These reviews remain up to date. Therefore, the goal of this chapter is to focus instead on open problems and the main issues of debate.

Accordingly, here we identify and discuss what we (the authors of this review) consider the top five bottlenecks in the field of planet formation. These are as follows:

1. What is the structure of protoplanetary disks? (section 2)
2. How did the first planetesimals form? (section 3)
3. How do planets migrate? (section 4)
4. What is the origin of the *trimodal* structure of the solar system? (section 5)
5. What is the relationship between terrestrial planets and super-Earths? (section 6)

These issues cover a range of size scales and time scales, and illustrate the upcoming challenges in planet formation. Our choice of the "top 5" is admittedly biased. Nonetheless, these issues are clear and present obstacles to our understanding of planet formation. We conclude this review in section 7 with a discussion.

2. What Is the Structure of Protoplanetary Disks?

Circumstellar disks of gas and dust represent the cradles of planet formation. The problem is to understand the mechanism by which protoplanetary disks evolve and transport mass to the central star [see, e.g., *Armitage*, 2011]. Depending on which mechanism is dominant, the resulting global disk structures may differ significantly (see Figure 1), with profound effects on planet formation and migration.

It has long been thought that transport of angular momentum in the disk is due to turbulent viscosity [*Shakura and Sunyaev*, 1973] and that the magnetorotational instability is the main source of turbulence [*Balbus and Hawley*, 1991]. With simple scaling arguments on the size of the vortices and their rotation period (or, equivalently, assuming that the stress tensor scales linearly with the local gas pressure), *Shakura and Sunyaev* [1973] modeled the viscosity ν as proportional to the square of disk's scale height H and to rotation

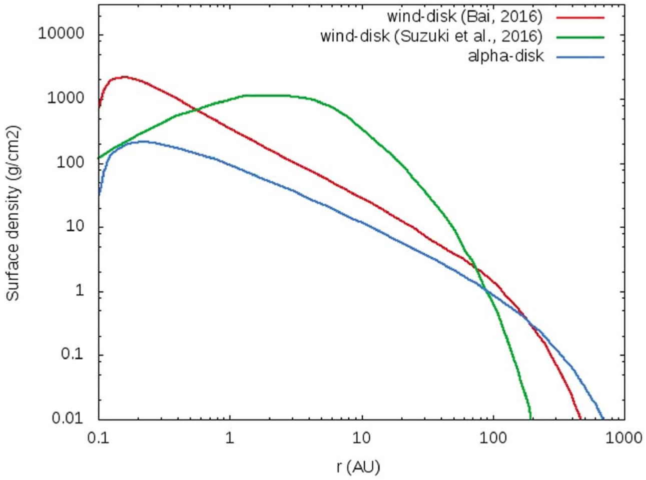

Figure 1. Structure of different disk models, all with an accretion rate on the star of $\sim 5 \times 10^{-9}\,M_\odot$/y. Each curve shows the surface density as a function of heliocentric distance. Two models of low-viscosity disks where transport is dominated by winds are shown, from *Bai* [2016] (red color; $\alpha = 2 \times 10^{-4}$) and *Suzuki et al.* [2016] (green color; $\alpha = 8 \times 10^{-5}$). They are labeled as "wind disks" to contrast with the classic α disk, whose density distribution is also shown in blue. In the α disk model the surface density of the gas scales inversely to the assumed viscosity (here $\alpha = 0.01$ is assumed). Note the depletion of gas in the inner part of the disk in the Suzuki et al. model.

frequency Ω: $\nu = \alpha H^2 \Omega$, where α is the proportionality coefficient. The assumption that α is the same everywhere leads to the so-called α disk model [*Lynden-Bell and Pringle*, 1974; *Pringle*, 1981; *Balbus and Papaloizou*, 1999]. The structure of these disks basically depends only on three parameters: the accretion rate of gas onto the central star, the value of α, and the dust/gas ratio, the latter governing the disk's opacity. The disk evolves under its own viscosity until the accretion rate on the star drops below a few times $10^{-9} M_\odot$/y. At this point the photoevaporation process becomes important, as it removes gas from ~1 AU at a comparable rate (see *Alexander et al.* [2014], for a review). Photoevaporation divides the disk into an inner part, rapidly accreted onto the star, and an outer part, rapidly photoevaporated inside-out; it explains the rapid final clearance of protoplanetary disks.

Stone et al. [1998] pointed out that Magneto Rotational Instability (MRI) is unlikely to act uniformly across the disk. The central part of the disk, which is opaque to radiation, should not be ionized and therefore the MRI should not operate there. This led to the concept of a "dead zone," a low-viscosity region within the disk. Disks with a dead zone can still be modeled with the α prescription, provided that α is a function of the radial and vertical coordinates. Because in the dead zone α is smaller, the gas density is much larger than in the MRI active zone to ensure the smooth transport of material through the disk. In disks modeled in 1-D (i.e., radial structure only) the contrast in gas surface density $\Sigma_{\rm dead}/\Sigma_{\rm MRI}$ is proportional to $\alpha_{\rm MRI}/\alpha_{\rm dead}$ [e.g., *Martin et al.*, 2012]. In 2-D models (r, z), however, there is no simple proportionality, because the gas can flow near the surface of the disk [*Bitsch et al.*, 2014b].

Recent studies have shown that the MRI is likely to be suppressed almost everywhere in the disk because of nonideal MHD effects such as ambipolar diffusion [*Bai and Stone*, 2013; *Lesur et al.*, 2014] (see *Turner et al.* [2014], for a review). Disk winds have been proposed to be the main process removing angular momentum from the disk, thus causing gas to accrete onto the central star [*Bai and Stone*, 2013; *Bai*, 2013, 2014, 2015, 2016; *Gressel et al.*, 2015; *Simon et al.*, 2015]. The resulting disk structure can be very different from that of an α disk. For instance, *Suzuki et al.* [2010, 2016] find that the inner part of the disk can be substantially depleted, although *Bai* [2016] still finds a $1/r$ surface density profile in the innermost ~10 AU, similar to that of an α disk. The actual surface density profile is very important for models of planetesimal formation and planet migration. For instance, a depleted inner disk would slow down (or even reverse) the radial migration of protoplanets [*Ogihara et al.*, 2015a, 2015b]. It would also have a much less sub-Keplerian rotation than an α disk, favoring particle accumulation and the formation of planetesimals.

An important question to address for a wind-dominated disk is how low the viscosity (or the turbulent strength) can be. There are sources of turbulence other than the MRI, such as the baroclynic instability [*Klahr and Bodenheimer*, 2003], the vertical shear instability [*Nelson et al.*, 2013], and the zombie-vortex instability

[*Marcus et al.*, 2015]. *Stoll and Kley* [2014] estimated that the vertical shear instability can sustain turbulence with a strength equivalent to $\alpha \approx$ a few times 10^{-4}, but more recent work [*Stoll and Kley*, 2016] argues that this is true only beyond ~5 AU. Thus, the actual strength of the turbulence and the associated viscosity in the inner disk is still unknown. The strength of turbulence is a key parameter for planetesimal growth, because it governs the settling of particles toward the midplane. The viscosity is also the key to estimate the temperature of the disk.

In fact, in the absence of viscous heating, the only source of heat is irradiation from the central star (Actually, *Gressel et al.* [2015] point out the existence of current layers at about $z = 2H$ which should generate heat. The role of these currents on the thermal structure of the disk is still unexplored.). A disk that is solely heated by the star is called a passive disk [*Chiang and Goldreich*, 1997; *Dullemond et al.*, 2001, 2002]. A passive disk is very cold throughout its evolutionary stages, until it becomes transparent to the stellar irradiation. *Chiang and Youdin* [2010] estimated that the snow line (the location where the temperature is 160–170 K so that water has a transition from vapor to solid state) in such a disk should be around ~0.4 AU. If this were the case, all bodies in the inner solar system should be water rich, including main belt asteroids and the Earth. While these bodies contain some water, their bulk water abundance is much less than that expected from solar abundance (about 50% in mass; [*Lodders*, 2003]), suggesting that the snow line was, at least during the early phases of the disk, much farther out than their location. In fact, the mechanisms proposed to explain why the inner solar system bodies did not accrete a lot of water as the disk cooled off [*Morbidelli et al.*, 2016; *Sato et al.*, 2016] require that the disk was initially too hot for the existence of water-ice at 1–2 AU. Thus, we expect that there was some nonnegligible turbulent viscosity in the inner disk, even if the origin of this viscosity is still not clear. For reference, for the snow line to be at about 3 AU, as suggested by asteroid composition, the viscous transport in the disk should have been about $3 \times 10^{-8} M_{\odot}$/y [*Bitsch et al.*, 2015a]. If the disk had this viscous transport at some point during its evolution, its viscosity had to be large or the disk very massive. See *Morbidelli et al.* [2016] for a more in depth discussion.

While it may seem tangential to planet formation, angular momentum transport and heating in protoplanetary disks are essential in determining the disk's structure. This feeds back into particle growth and orbital migration.

3. How Did the First Planetesimals Form?

The solid building blocks of planets are a trace component within gas-dominated protoplanetary disks. The processes that govern the growth of macroscopic particles remain poorly understood. Perhaps the most vexing problem is the growth of the first planetesimals. Once planetesimals are present in the disk, their further growth by accreting pebbles is modestly well understood. The first population of planetesimals may serve as a planetary system's blueprint.

In the classic model of planet accretion, dust particles settle to the midplane of the disk, collide with each other, and form aggregates held together by electrostatic forces [e.g., *Dominik and Tielens*, 1997]. Little by little these aggregates grow and get compacted by collisions, forming small planetesimals [e.g., *Weidenschilling and Cuzzi*, 1993, *Blum and Wurm*, 2008].

Today we know that this classic picture of planetesimal growth has severe problems (illustrated in Figure 2). When silicate grains grow to a size of about a millimeter, they start to bounce off each other instead of accreting [*Zsom and Dullemond*, 2008; *Güttler et al.*, 2009]. In the icy part of the disk, particles can grow up to a few decimeters in size before starting to bounce. This is called the *bouncing barrier*. At these sizes, particles migrate rapidly in the disk toward the star due to gas drag. This radial drift produces large relative velocities among particles of different sizes and hence disruptive collisions. Even if collisions were not disruptive and particles could continue to grow, eventually meter-size boulders would migrate so rapidly to be lost into the star before they can grow significantly further [*Weidenschilling*, 1977]. This is the well known *meter-size barrier* (referred to as the "drift barrier" in Figure 2).

Over the past decade new ideas have been proposed to overcome this problem. On the one hand, it has been shown [*Okuzumi et al.*, 2012; *Kataoka et al.*, 2013] that the regime of collisional coagulation might nevertheless work beyond the snow line because of the tendency of icy particles to form very fluffy aggregates. These aggregates, thanks to their extremely high porosity, are very resistant to collisional disruption and their radial drift in the disk is also very slow. Thus, both the bouncing/breaking barrier and the drift barrier can be

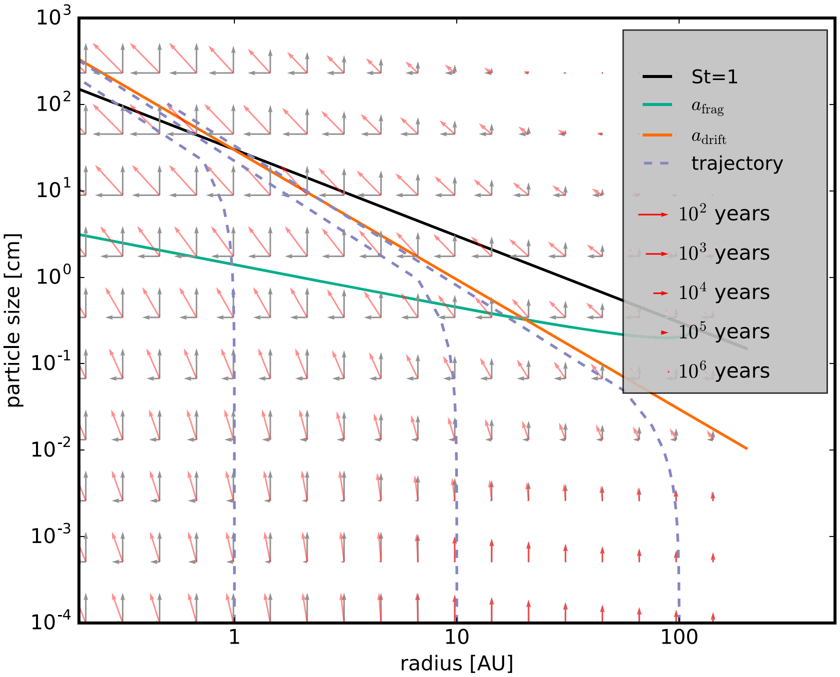

Figure 2. Growth and drift of particles in a protoplanetary disk. Trajectories for the growth (vertical arrows) and inward aerodynamic drift (horizontal arrows) were calculated at each point in a specific disk model, with a $1/r$ surface density profile and dust-to-gas ratio of 0.5% [*Birnstiel and Andrews*, 2014]. The arrow length is inversely proportional to the relevant logarithmic timescales; i.e., to $a/\dot{a}$ (for inward drift) and $r/\dot{r}$ (growth). The green curve shows the fragmentation barrier above which growth is inhibited. The dashed/purple curves show the trajectories of particles starting at different orbital radii (calculated neglecting fragmentation). The orange curve is the corresponding drift barrier. The solid black curve denotes where the Stokes number is equal to 1. From *Birnstiel et al.* [2016].

circumvented and kilometer-size planetesimals can be formed after a final phase of contraction of the aggregates. This alleged formation path for planetesimals, however, should not work within the snow line, due to the reduced sticking properties of the silicate grains.

On the other hand, it has been shown that "small" particles (whatever their chemical nature) tend to clump due to turbulence in the disk [*Cuzzi et al.*, 2001; *Johansen et al.*, 2007]. Once the clump is sufficiently dense, its self-gravity can take control, holding all particles together until they settle in their common potential well and form a large planetesimal [*Johansen et al.*, 2007; *Cuzzi et al.*, 2010]. This recipe, however, is not without problems. First, it requires turbulence within the disk. Yet the very existence of turbulence and its properties are far from being firmly established, as discussed in the previous section. Second, in order to clump under the effect of turbulence, particles must be much larger than that allowed by the bouncing barrier, at least in the inner disk. In fact, the critical parameter governing the dynamics of a particle undergoing gas drag is its Stokes number $S_t = t_f\Omega$, where Ω is the Keplerian frequency and $1/t_f$ is the coefficient relating the acceleration of the particle due to the drag to the velocity difference between the particle and the fluid medium, i.e., $\dot{v}_{\mathrm{p}} = 1/t_f(v_{\mathrm{p}} - v_{\mathrm{gas}})$. In the simulations by *Johansen et al.* [2007], particles efficiently clumped have Stokes number (i.e., the product of the friction time and the orbital frequency) larger than 0.5 which, at 1 AU, corresponds to sizes of ~20 cm. The concentration mechanism in low-vorticity regions proposed by *Cuzzi et al.* [2001] seemed to operate for chondrule-sized particles, but a new reconsideration of this mechanism [*Cuzzi et al.*, 2016], adopting an improved turbulent cascade model, also raises the particle size to 10 cm or so. How particles can grow to this size in the inner disk is an open problem.

In order to relax the hypothesis that the disk is a priori turbulent, it has been proposed that particles themselves can generate turbulence and then clump in a feedback process. Two mechanisms can produce this result. The sedimentation of particles toward the midplane of the disk can drive a Kelvin-Helmoltz instability, because the particles force the midplane layer of the gas to rotate around the Sun faster than the surface layers [*Weidenschilling*, 1995]. As shown in *Johansen et al.* [2006], the turbulence generated by the Kelvin-Helmholtz instability can clump the particles enough to form self-gravitating clusters. But, again, this effect depends on particle size. Small particles do not sediment very fast and therefore do not create a dense midplane layer; moreover, being more coupled with the gas, the shear effect that they generate is weaker. Effective clumping leading to local sold/gas density ratio of a few tens is observed only for particles with Stokes number larger than 0.1, which corresponds to a size of 10 cm at 1 AU.

The second mechanism is the streaming instability [*Youdin and Goodman*, 2005]. This is a linear instability generated by the radial drift of particles. When the local density of particles exceeds the background density (i.e., a small clump is formed due to some statistical density fluctuation), the collective drag force exerted by the clump on the gas makes the disk rotate faster; as a consequence, the clump as a whole drifts inward slightly more slowly than individual particles. This creates a sort of traffic jam. Other particles drifting inward at the nominal speed catch up to the clump, enhance the local overdensity of solids, and further decelerate the radial drift of the clump. Thus, the local accumulation of particles speeds up, and so forth in a positive feedback. Yet the streaming instability is not without problems. If particles are relatively large (Stokes number larger than 0.1), clumping is effective only if the solid/gas surface density ratio is larger than 3% (so, enhanced compared to solar value of 1% [*Johansen et al.*, 2009]). For chondrule-sized particles in the inner disk, the solid/gas ratio has to be increased above 8% [*Carrera et al.*, 2015].

Models of particle coagulation and radial drift [*Lambrechts and Johansen*, 2014] show that both the size of available particles and the solid/gas ratio decrease in time even as the gas surface density decays. It is unclear whether the conditions for the streaming instability can ever be reached. According to *Drążkowska and Dullemond* [2014] the streaming instability may only be operational in the outer disk for two reasons: (i) beyond the snow line, the sticky properties of ice allow the formation of larger particles and (ii) for a given particle size, the Stokes number is larger than that in the inner disk. In the inner disk the streaming instability may only operate in a relatively narrow ring [*Drążkowska et al.*, 2016] where pebbles pile up if the radial surface density profile of the disk is sufficiently shallow.

The high solid/gas ratio required for chondrule-sized particles to clump in the asteroid belt can only be reached in the late stage of the disk, after a substantial fraction of the gas has been removed [*Throop and Bally*, 2005] and *if* particles are regenerated by some process, for instance, in planetesimal-planetesimal collisions.

The analysis of meteorites shows indeed that there were at least two generations of planetesimals in the inner disk. The parent bodies of iron meteorites formed early, in the first million years [*Kruijer et al.*, 2012] after the formation of the first solids (the Calcium-Alluminium Inclusions, CAIs, dated to have formed 4.568 Gy ago [*Bouvier et al.*, 2007a; *Burkhardt et al.*, 2008]). In contrast, the parent bodies of chondritic meteorites formed after 3–4 Ma [*Villeneuve et al.*, 2009]. It is unclear whether there was a gap in time in planetesimal formation and even whether the first and last generations of planetesimals formed in the same place. Today, all meteorites come from the asteroid belt, but the asteroids may have been trapped into the belt from different original reservoirs [*Bottke et al.*, 2006; *Levison et al.*, 2009; *Walsh et al.*, 2011; *Raymond et al.*, 2016]. Some authors have proposed that chondrules are the outcome of collisions among massive objects [*Libourel et al.*, 2006; *Asphaug et al.*, 2011; *Johnson et al.*, 2015]. All this may be suggestive that the first planetesimals formed only at select locations (near the disk's inner edge or beyond the snow line) and that elsewhere planetesimals only formed later, as the protoplanetary disk evolved toward the debris disk phase. But this is still far from a consolidated view. It is not clear, for instance, why the second-generation asteroids would have only accreted chondrules and not a spectrum of collisional debris with different physical and chemical properties.

Once planetesimals are formed, as long as they are embedded in a disk of gas and drifting particles and they are big enough (typically larger than 100 km), they can keep growing by accreting the particles via a combination of gravitational deflection and gas drag [*Ormel and Klahr*, 2010; *Johansen and Lacerda*, 2010; *Lambrechts and Johansen*, 2012, 2014; *Guillot et al.*, 2014; *Johansen et al.*, 2015; *Levison et al.*, 2015a; *Visser and Ormel*, 2016]. This process is called *pebble accretion* and it is now fairly well understood and recognized to play a fundamental role in planet formation. Unfortunately, by definition, pebble accretion operates only after that the first planetesimals are formed. Thus, our poor understanding of the primary planetesimal formation process, discussed above, blocks our understanding of when, where, and in which numbers protoplanets formed in the disk.

4. How Fast, and in What Direction, Do Planets Migrate?

Growing planets interact gravitationally with the protoplanetary disk. They create a spiral density wave in the gas distribution that is stationary in the reference frame rotating with the planet [*Ogilvie and Lubow*, 2002]. In turn, this nonaxisymmetric density distribution exerts a torque on the planet. As a result, the angular momentum of the planet's orbit changes and the orbit expands or contracts depending on the sign of the torque. In other words, the planet undergoes a radial migration. It can be demonstrated that in disks whose surface density is a power law of $1/r$ the torque is negative, and hence, the planet migration is directed toward the central star [*Ward*, 1997]. For low-mass planets, the migration speed scales linearly with the planet's mass [*Goldreich and Tremaine*, 1980; *Lin and Papaloizou*, 1986]. Thus, planet migration can be neglected up to, at most, Mars mass embryos, such as the precursors of terrestrial planets [*Wetherill*, 1990]. According to *Tanaka et al.* [2002], the migration time scale of a Mars mass body at 1 AU in a minimum-mass solar nebula (MMSN) disk is 1 Ma. Given that these bodies took themselves a few million years to form [*Dauphas and Pourmand*, 2011], it is likely that they emerged in a disk less massive than the MMSN and therefore did not migrate significantly during the disk phase. For this reason, terrestrial planet formation models typically neglect radial migration. But for protoplanets of one to few Earth masses, such as the growing cores of giant planets, migration cannot be ignored.

The discovery of hot Jupiters [*Mayor and Queloz*, 1995] was welcomed as a proof of planet migration [*Lin et al.*, 1996]. But it was soon understood that the hot Jupiters are the exception rather than the rule, as most extrasolar giant planets have orbital radii of 1–2 AU [*Butler et al.*, 2006; *Udry and Santos*, 2007]. In order to reproduce the observed distribution of planets, planet synthesis models [e.g., *Ida and Lin*, 2004a, 2004b; *Alibert et al.*, 2005] had to artificially reduce the speed of migration by 1 to 2 orders of magnitude relative to theoretical expectations.

No mechanism to globally reduce planets' migration speed across the disk has been found. Detailed studies have identified effects that can reduce, stop, and even reverse migration, but only at specific locations. *Masset et al.* [2006] found that a positive surface density gradient in the disk can act as a trap for migrating planets. However, the only place where such a gradient is expected is at the inner edge of the disk (or at the boundary between the MRI active region and the dead zone of the disk, which is also very close to the star). The mechanism of *Masset et al.* [2006] can explain why planets do not fall on the star but accumulate on small semimajor axis orbits; however, it cannot explain how the planets that are a few astronomical units away could have avoided migrating closer to the star.

Paardekooper and Mellema [2006] found a positive torque that arises in nonisothermal disks with steep temperature gradients. This torque can exceed the negative one exerted by the spiral density wave mentioned above, thus forcing the outer migration of the planet. Several years of studies led to a quantitative analysis of this torque [*Paardekooper et al.*, 2010, 2011]. When applying these torque formulae to the structure of an α disk [*Hasegawa and Pudritz*, 2011; *Hellary and Nelson*, 2012; *Bitsch et al.*, 2015a], it is found that the outward migration region is confined in radial range and planet mass (see Figure 3). In a massive young, warm disk, the main region of outward migration extends from 3 to 9 AU and encompasses planets between 5 and 50 Earth masses (see Figure 3). This is good news, because it means that a planet in this mass range, migrating from the outer disk, would stop at the outer border of this region. But later on, when the disk becomes cooler and less massive, the region of outward migration shifts inward and to smaller planet masses (Figure 3). Bodies more massive than 10 Earth masses are released to rapidly migrate inward. For low-viscosity, MRI inactive disks (see section 2), the maximal planet mass of the outward migration region is even smaller. For multiple planets the situation may be even worse. Mutual interactions among the planets may raise their orbital eccentricities, and in this case the aforementioned positive torque is strongly reduced, promoting inward migration [*Bitsch and Kley*, 2010; *Hellary and Nelson*, 2012].

The currently favored paradigm of giant planet formation proposes that 10–20 Earth mass cores serve as the seeds for gas giants [*Pollack et al.*, 1996]. There is a delay between the core's growth and the onset of rapid gas accretion. During this interval massive cores may migrate inward and, following current models, will reach the inner edge of the disk before becoming giants [*Coleman and Nelson*, 2014]. With our current understanding of migration, for giant planets to form and still be at a few astronomical units from the star when the disk disappears, *Bitsch et al.* [2015b] found that their cores must start their growth at 15–20 AU and relatively late during the disk lifetime. Yet issues remain regarding this result. Because the outer disk is flared, both the streaming instability and pebble accretion are more efficient closer in than farther out. Thus, it is difficult to

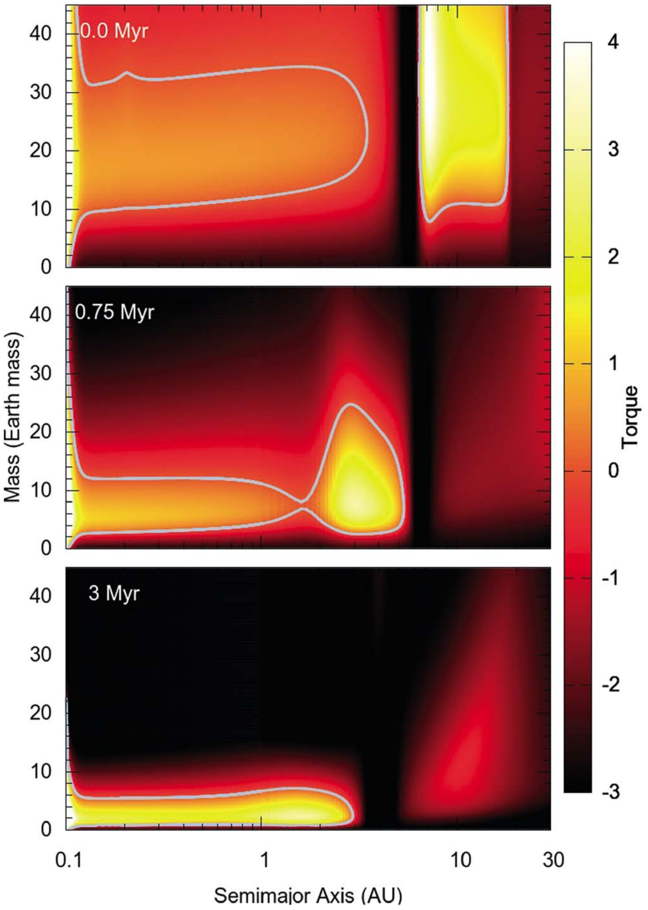

Figure 3. A migration "map" for an evolving protoplanetary disk. In each snapshot, the color denotes the torque felt by a planet of a given mass at a given orbital radius. A positive torque will cause the planet to migrate outward and a negative torque to migrate inward. Contours follow zero-torque locations and enclose regions of outward migration. In the first snapshot there are two distinct zones of outward migration, which merge into one that moves inward and to lower masses as the disk evolves. The disk was modeled using the α prescription [*Shakura and Sunyaev*, 1973] with $\alpha = 5 \times 10^{-3}$. From the disk model of *Bitsch et al.* [2015a].

understand why giant planet cores could not form between the original snow line location (say 3–5 AU) and 15 AU, if they could form beyond this threshold distance. One possibility is that planets that formed closer in or earlier were engulfed into the central star and that the planets that we see today are the "last of the Mohicans," namely, those that formed the last and the farthest, so that they could not reach the star before disk removal [*Lin*, 1997; *Laughlin and Adams*, 1997]. But this is difficult to believe: the abundance of numerous close-in super-Earths argues that planets stop migrating at the inner edge of the disk [*Masset et al.*, 2006] and do not fall onto the star; indeed, disks have inner edges that stop inward migration [*Romanova et al.*, 2013; *Bouvier et al.*, 2007b]. Moreover, in our Solar System it is hard to conceive that numerous planets migrated through the inner disk without leaving a trace of their passage. The case of our solar system may be helped by the fact that the contemporary presence of Jupiter and Saturn in nearby orbits reverses the migration direction of these giant planets [*Masset and Snellgrove*, 2001]. But even in this case, *Bitsch et al.* [2015b] could not achieve the required Jupiter-Saturn configuration if these planets started growing within 23 AU.

It is likely that we are still missing a fundamental piece of the migration story. One idea is that, if disks are much less viscous than expected (see section 2) relatively small planets could open gaps in the gas distribution. They would then migrate in a different regime, known as the Type II regime [*Lin and Papaloizou*, 1986], in which the migration speed is equal to the radial speed of the gas due to its viscous evolution. If the viscosity of the disk is small, this speed is also small. However, this idea seems naive. First, to open a gap in the gas distribution, it is not enough that the torque exerted by the planet overcomes the viscous torque within the disk; it is also needed that the planet has a Hill radius larger than the scale height of the disk [*Crida et al.*, 2006; *Morbidelli et al.*, 2014]; otherwise, the gas flows into the gap from the vertical direction. Second, Type II migration is an ideal process, but in reality gap-forming planets do not migrate at the viscous radial-drift speed [*Duffell et al.*, 2014; *Dürmann and Kley*, 2015]. In particular, in the low-viscosity regime migration is faster than the radial drift of the gas.

Additional positive torques exerted on the planets have been searched for in the last years. *Benítez-Llambay et al.* [2015] found that a few Earth mass planet with a very high temperature because of a vigorous accretion of solids can migrate outward. However, this effect wanes in the mass regime of giant planet cores, so it does not help the giant planet formation problem [*Bitsch et al.*, 2015b]. *Fung et al.* [2015] claimed to have found a new positive torque arising only in 3-D simulations of planet-disk interactions. However, this torque seems to disappear when simulations are conducted with a sufficiently high resolution. Thus, nothing promising is in view at the current time.

Maybe it is the disk structure that is misleading us [*Coleman and Nelson*, 2016]. As we saw in section 2 the accretion α disks that are usually considered may not be realistic. If the new disk-wind paradigm of transport creates a global positive surface density gradient in the inner few astronomical units of the disk, as advocated by *Suzuki et al.* [2010], the migration of planets can be substantially modified [*Ogihara et al.*, 2015a, 2015b]. However, it is not yet sure that this disk structure is real [see *Bai*, 2016]. More work on the disk structure is needed.

5. What Is the Origin of the Solar System's Peculiar Orbital Structure?

The solar system is characterized by a trimodal structure. In its inner part there are the terrestrial planets, rocky and relatively small. Farther out, there is the asteroid belt, which carries cumulatively a negligible mass (about 5×10^{-4} Earth masses). Beyond 5 AU lies the realm of the giant planets. The formation of the terrestrial planets requires that during the lifetime of the protoplanetary disk, a set of planetary embryos formed in that region, with approximately the mass of Mars. Mars itself could be a surviving embryo [*Dauphas and Pourmand*, 2011]. The small mass ratio between Mars and the Earth suggests a substantial depletion in the total mass of solid beyond 1 AU and across the asteroid belt [*Hansen*, 2009; *Raymond et al.*, 2009], established very early during the history of the solar system. In contrast, the formation of the giant planets requires the accretion of solid cores of 10–20 Earth masses before the removal of gas.

How this trimodal structure was set is still an issue of open debate. *Walsh et al.* [2011] proposed that the depletion in solid mass beyond 1 AU was caused by a specific pattern of Jupiter's migration. Keeping in mind the caveats discussed in the previous section, it is legitimate to postulate that Jupiter initially migrated inward, when it was basically alone in the disk and then reversed migration direction when Saturn formed ([*Masset and Snellgrove*, 2001; *Morbidelli and Crida*, 2007; *Pierens and Nelson*, 2008; *Pierens and Raymond*, 2011]; discussed at length in *Raymond and Morbidelli* [2014]). If this inward-then-outward migration history brought Jupiter down to ~1.5 AU before bringing it into the outer disk again, the region beyond 1 AU would have been strongly depleted in mass (Figure 4). Indeed, the simulations of Walsh et al. show that the terrestrial planets would have formed with a mass distribution very similar to the one observed (see also *Jacobson and Morbidelli* [2014]), and the asteroid belt would have acquired a structure consistent with the current one [see *Deienno et al.*, 2016]. If this scenario, dubbed "Grand Tack" is correct, then the solar system had initially just a bimodal structure, with Mars mass planetary embryos inside of the snow line and giant planet cores outside; the trimodal structure (i.e., the depletion between 1 AU and the orbit of Jupiter) was generated by Jupiter's migration (Figure 4).

However, even this bimodal structure is puzzling. Assuming that planetesimals formed everywhere in the disk with comparable masses (but see section 3), the subsequent process of planet growth by pebble accretion should favor the bodies closer to the Sun [*Ida et al.*, 2016]. In other words, giant planet cores should have formed in the inner disk and Mars mass embryos in the outer disk! The only exception to this is if the pebble sizes drastically changed at the snow line. *Morbidelli et al.* [2015] postulated that beyond the snow line the pebbles were decameter-size objects made of ice and silicate grains. When these pebbles drifted across the snow line the ice sublimated: 50% of the solid mass was lost and small (millimeter-size) silicate grains were released (see also *Saito and Sirono* [2011]). If there was enough turbulence in the disk to make the particle layer thicker than the Hill radii of the planetesimals (a weak turbulence with $\alpha = 10^{-4}$ would have

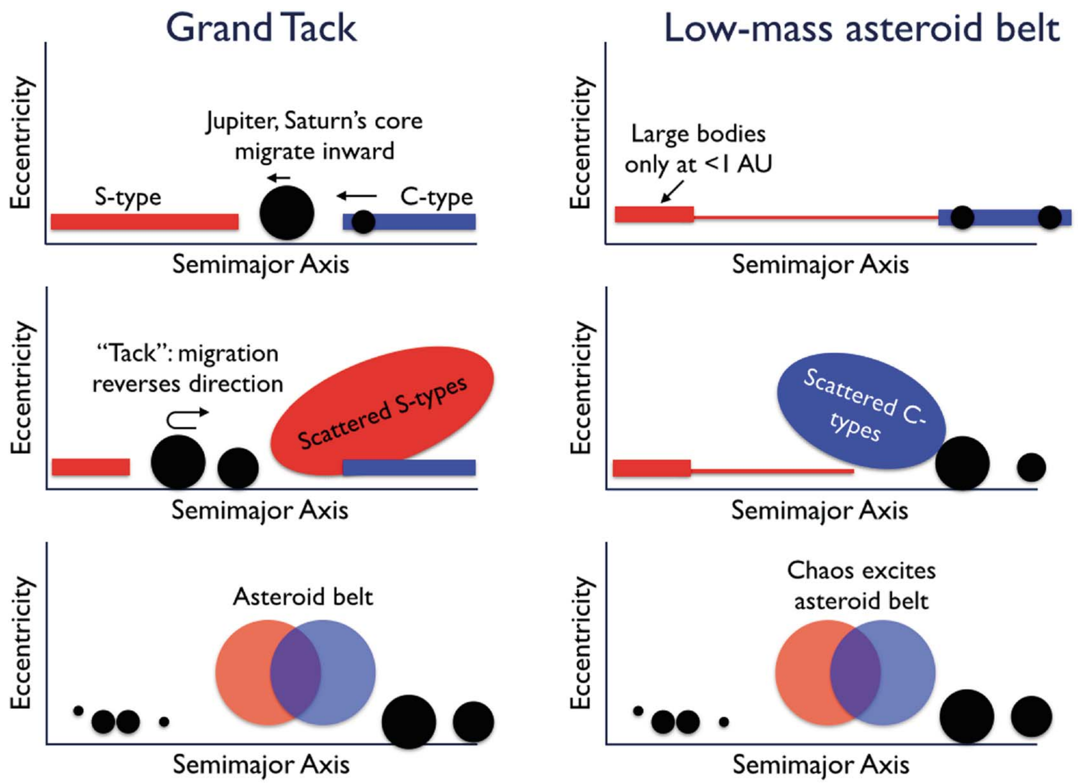

Figure 4. Cartoon representation comparing (left) the Grand Tack model with (right) a model in which the asteroid belt was low mass even at early times. While the evolution of the two models is quite different, each can match the present-day inner solar system.

been sufficient), the accretion of small grains would have been much less efficient than the accretion of large pebbles. Hence, two initially equal-mass planetesimals on either side of the snow line would have grown at drastically different rates: by the time the outer one reached 20 Earth masses, the inner one would have barely reached Mars mass [*Morbidelli et al.*, 2015; *Ida et al.*, 2016]. This explanation of the bimodal structure of the Solar System, however, is not unique: if planetesimals inside the snow line were smaller for some reason (see section 3) than planetesimals beyond the snow line, the latter would have grown much faster by pebble accretion even without a drastic change in pebble size across the snow line.

But let us take a step back and wonder whether the trimodal structure of the solar system could have been primordial (i.e., not the consequence of a Grand Tack-like migration of Jupiter). Starting from a smooth population of planetesimals, *Levison et al.* [2015b] obtained a concentration of mass inside of 1 AU through pebble accretion. Their model involves a number of assumptions, three of which appear particularly critical to us. First, it is assumed that there is no mass flux in solids coming from beyond the snow line; second, pebbles form by condensation and coagulation throughout the inner disk; third, the disk is flared everywhere. The first and the second assumptions together have the consequence that the closer a planetesimal is to the snow line (but inward of its location), the smaller the pebble flux that crosses its orbit. The third assumption makes the pebble accretion process more efficient with decreasing heliocentric distance.

These three assumptions may not be well justified. Preventing a flux of pebbles from the outer disk requires the formation of a strong positive gas surface density gradient (i.e., a pressure "bump") at the snow line. It has been proposed in the context on an analytic 1-D (radial) disk model [*Kretke and Lin*, 2007] that the snow line can create a pressure bump because the condensation of icy grains could strongly reduce the ionization of the gas, quench its turbulent viscosity, and increase the gas surface density beyond the snow line. However, 3-D numerical simulations of disk structure in the presence of radial and vertical viscosity transitions [*Bitsch et al.*, 2014b] show that this is true only if $\frac{\mathrm{d}\log(\nu)}{\mathrm{d}\log(r)} < -28$, where ν is the viscosity. It is very unlikely that the condensation of icy grains could have such a dramatic effect on the viscosity. As for the second assumption, it has been shown that the direct condensation of gas is not relevant after about half a viscous time scale [*Morbidelli et al.*, 2016]. In fact, after this time, the gas drifts inward faster than the radial displacement of the condensation lines. So when the temperature drops at a given location the local gas should not carry any condensable species because that species would have already condensed farther out. Concerning the third assumption, a warm disk with a snow line at ∼5 AU, as in the Levison et al. model, must be dominated by viscous heating in its inner parts (see section 2), but viscously dominated disks are not flared [*Kenyon and Hartmann*, 1987; *Chiang and Goldreich*, 1997; *Bitsch et al.*, 2014a]. Having a flared disk in the inner part would require an ad hoc radial dependence of the dust/gas ratio [*Levison et al.*, 2015b].

Nevertheless, the possibility that the solid mass was concentrated within 1 AU should be taken seriously. As discussed in section 3 it is possible that the streaming instability formed a first generation of planetesimals in just two places: near the inner edge of the disk (although it is unclear if this could extend out to 1 AU) and beyond the snow line. If this was the case, obviously, pebble accretion could only operate in these regions. Asteroids may have only formed later, as a low mass second-generation population, from the collisional debris of the first generation. Although this view is far from being established, it would explain the trimodal structure of the solar system without the need for the Grand Tack.

Not being able to decide a priori which view is the most realistic for the formation of the solar system, we can turn to observational constraints to discriminate them. *Izidoro et al.* [2015c] pointed out that in the absence of Jupiter's migration, an initially low-mass asteroid belt should have remained dynamically cold, i.e., most asteroids should have today low eccentricity, low inclination orbits. This contrasts with the observed distribution. However, in a more recent work [*Izidoro et al.*, 2016] it was found that if the giant planets had a secular chaotic motion (which might have happened, for instance, if Jupiter and Saturn spent some time in their mutual 1/2 resonance after the removal of the gas from the protoplanetary disk), the orbital distribution in the asteroid belt could have been excited by the stochastic stirring exerted by a multitude of secular resonances. Thus, the asteroid belt does not seem to be diagnostic of what really happened, given that its structure can be explained by both the Grand Tack model and by chaotic stirring (Figure 4).

Therefore, we probably need to turn to the terrestrial planets for more insight. The amount of water-rich material incorporated by the terrestrial planets in the two scenarios may be significantly different, although this has not been thoroughly explored. Another issue to investigate is the final orbital excitation of the terrestrial planets. *Levison et al.* [2015b] investigated the growth of terrestrial planets from a local annulus of planetary embryos and planetesimals. They find that the final terrestrial planet systems have angular momentum deficits (AMD: a mass-weighted mean of the eccentricities and inclinations of the planets [*Laskar*, 1997]) that is 2 to 10 times that of the real terrestrial planets. The reason for this is that the systems of planetary embryos deplete nearly all planetesimals before having any major orbital instability that allows embryo-embryo merging. This leaves behind insufficient mass in planetesimals to significantly damp the orbits of the final planets [*O'Brien et al.*, 2006; *Raymond et al.*, 2006]. If this is confirmed by future studies including also the ejection of debris in embryo-embryo collisions, it could become a strong argument in favor of the Grand Tack hypothesis (or another mechanism that injects planetesimals into the inner disk). In fact, during the inward migration of Jupiter in the Grand Tack model, a large number of planetesimals are transported from the asteroid belt into the terrestrial planet region [*Walsh et al.*, 2011]. This repopulates the terrestrial planet region of planetesimals, which then damp the eccentricities and inclinations of the forming planets by dynamical friction, allowing the final system to meet the AMD constraint [*Jacobson and Morbidelli*, 2014].

6. Are Super-Earths and Terrestrial Planets the Same or Different?

So-called "super-Earths" are the most abundant class of planets known to date. Exoplanet searches have found that roughly half of all Sun-like stars have one or more planets with radii of 1–4 Earth radii and orbital periods shorter than ∼100 days [*Mayor et al.*, 2011; *Howard et al.*, 2012; *Fressin et al.*, 2013; *Petigura et al.*, 2013].

What can we learn about planet formation from the population of super-Earths? (For simplicity, in this discussion we refer to all exoplanets smaller than 4 $R_\oplus$ and with orbital periods shorter than 100 days as *super-Earths*.) Super-Earths are often found in multiple systems, usually in compact orbital configurations with low eccentricities and low mutual inclinations [*Lissauer et al.*, 2011; *Fabrycky et al.*, 2014; *Tremaine and Dong*, 2012; *Fang and Margot*, 2012]. Their orbital separations—measured in orbital period ratio or in mutual Hill radii—are similar to those among the solar system's terrestrial planets [*Fang and Margot*, 2013]. It is thus tempting to imagine that these planets formed by the same processes as the terrestrial planets, via in situ growth of rocky planetesimals or planetary embryos. Invoking the ad hoc existence of a large population of embryos close to

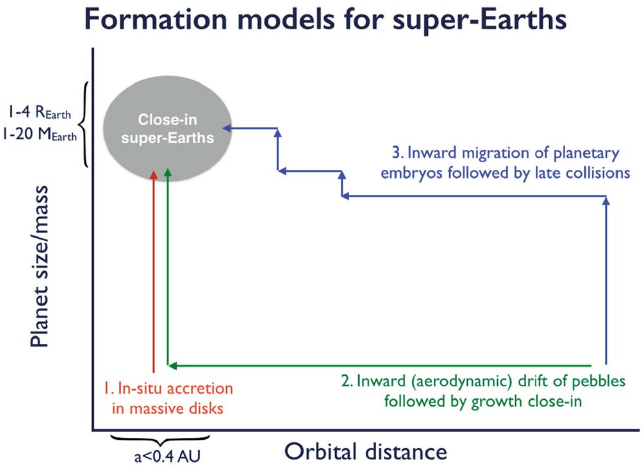

Figure 5. Illustration of the different formation models for super-Earths.

their stars can indeed reproduce some properties of the observed super-Earth systems [*Hansen and Murray*, 2013] (Figure 5). However, the in situ accretion hypothesis fails for several reasons. First, if super-Earths formed locally, then one can construct a “minimum-mass extrasolar nebula” (MMEN) to understand the distribution of solids close to the star ([*Raymond et al.*, 2008; *Chiang and Laughlin*, 2013]; note that *Kuchner* [2004] built an analogous nebula using close-in giant exoplanets). But the MMEN is both extremely dense (1 – 2 orders of magnitude more massive than the nebula inferred from the solar system or from observations of disks around young stars [*Andrews et al.*, 2009; *Williams and Cieza*, 2011]) and inconsistent among different systems, with a broad range of surface density profiles [*Raymond and Cossou*, 2014; *Schlichting*, 2015]. It is difficult to reconcile such a nebula with the structure of an actual protoplanetary disk. Second, whereas migration of planetary embryos had a limited effect for Mars mass planetary embryos in the primordial solar system, migration cannot be ignored in the case of super-Earths. Given the super-Earths’ higher masses and closer proximity to their stars (which likely translates into higher gas densities), the time scales for orbital migration are extremely short [*Ogihara et al.*, 2015a]. In fact, in the in situ accretion model the inner disk was so dense that even the time scale for in-spiraling of embryos due to aerodynamic drag was shorter than the disk lifetime [*Inamdar and Schlichting*, 2015]. This means that even if the super-Earths formed in situ, their orbits must have changed. In other words, super-Earths could not have formed in situ in the strictest sense.

It is nevertheless possible that super-Earths grew from solids that were transported inward. Yet the size scale of inward transported solids remains debated. *Moriarty and Fischer* [2015] proposed that super-Earths formed from in situ planetesimals which efficiently accreted pebbles flowing from the outer disk. The model of *Chatterjee and Tan* [2014] (see also *Chatterjee and Tan* [2015] and *Hu et al.* [2016]) instead does not require the preexistence of planetesimals in the inner disk, but proposes that pebbles drifted inward and were trapped at the inner boundary of the dead zone (Figure 5). When enough mass was trapped, gravitational instability was triggered that led to the formation of a planet. The dead zone receded, pebbles were trapped farther out at this new location, and the process continued. The pebble drift model is appealing in its simplicity yet has only been explored in simple analytical terms. While promising, the actual trapping, growth, and subsequent orbital migration of super-Earths by this mechanism needs further study.

An alternate model proposes that the inward transport occurred at larger size scales via protoplanet migration [*Terquem and Papaloizou*, 2007; *Ogihara and Ida*, 2009; *McNeil and Nelson*, 2010; *Ida and Lin*, 2010; *Cossou et al.*, 2014] (Figure 5). Planetary embryos similar to those that built the cores of the giant planets formed at orbital radii of a few to a few tens of astronomical units. Embryos migrated inward until they reached the inner edge of the disk. Embryos piled up and their orbits formed a chain of mean motion resonances (sometimes with a planet pushed interior to the disk’s inner edge). When the gas disk dissipated (and its dissipative effects disappeared), some of the resonant chain destabilized, particularly those where the number of planets of the resonant chain was larger than a threshold value [*Matsumoto et al.*, 2012]. These destabilized systems suffered a late stage phase of giant collisions between embryos. With very simple assumptions the surviving planets quantitatively match the observed distributions [*Cossou et al.*, 2014; *Ogihara et al.*, 2015a]. This also predicts that some systems of super-Earths — those that avoided late instabilities — should survive in resonant chains such as the recently identified four-planet resonant chain in the Kepler-223 system [*Mills et al.*, 2016].

While effective and simple, the migration model is built on two other models that have their own uncertainties. First, it relies on the rapid formation of a population of planetary embryos [see *Lambrechts and Johansen*, 2014; *Morbidelli et al.*, 2015]. The formation of super-Earths in the context of realistic pebble accretion of embryos has not been simulated self-consistently to date. Second, the migration model is built on the current generation of migration maps [e.g., *Bitsch et al.*, 2015a], which are themselves at the mercy of the structure and evolution of the disk (see sections 2 and 3). This illustrates the interdependence of the different problems in planet formation.

We now turn our attention to the question of similarities and differences between super-Earths and the solar system's terrestrial planets. We have access to a plethora of data regarding the terrestrial planets including exquisite orbital constraints on the inner and outer planetary system, geochemical measurements (for Earth and Mars), seismological data (for Earth), and a host of other information. While we can imagine extrapolating our understanding of our solar system, we cannot hope to obtain similar data for planets around other stars in a foreseeable future.

The key question remains as follows: In making an analogy between our terrestrial planets and super-Earths, would we be comparing apples with apples?

Regardless of how they form, super-Earths grow much faster than Earth. Earth's accretion concluded (i.e., it reached ~99.5% of its final mass) with a final giant impact that is thought to have created the Moon [*Benz et al.*, 1986; *Canup and Asphaug*, 2001] roughly 50–150 Myr after the start of planet formation [*Kleine et al.*, 2009; *Jacobson et al.*, 2014]. Accretion times close to the star are extremely short, and simulations show that Earth-sized or larger planets grow within 0.1–1 Myr [*Lissauer*, 2007; *Raymond et al.*, 2007; *Bolmont et al.*, 2014; *Ogihara et al.*, 2015a]. And any migration must of course have taken place during the gaseous disk phase, which lasted a few Myr ([*Haisch et al.*, 2001; *Hillenbrand*, 2008], but see *Pfalzner et al.* [2014], for a different view). The orbital spacing of super-Earths is suggestive of a final phase of instability [*Cossou et al.*, 2014; *Pu and Wu*, 2015], which may have been triggered by the dissipation of the gaseous disk [*Ogihara and Ida*, 2009] and would have concluded within a few million years.

Raymond et al. [2014] proposed a distinction between super-Earths and "giant embryos," the difference being that giant embryos would have been fully formed while the gas was still present in the disk. Perhaps a clearer division would be between planets that become massive enough to migrate while the disk is still present and those that do not. The vast majority of observed super-Earths are massive enough that the inferred migration time scales are much shorter than the typical disk lifetime [*Rogers et al.*, 2011; *Swift et al.*, 2013]. However, a handful of systems host planets so small that their migration time scales are very long (e.g., the Kepler-444 system [*Campante et al.*, 2015]). In principle, very small planets must have been built from solids that did not migrate; rather, they either accreted in situ or drifted inward as pebbles.

The solar system's terrestrial planets were built from embryos that presumably did not migrate significantly, whereas super-Earths grew from migrating embryos. One might imagine that variations in the protoplanetary disk mass could put super-Earths and the terrestrial planets in the same context. Low-mass disks should form small embryos that do not migrate much whereas high-mass disks should form larger embryos that migrate significantly [e.g., *Kokubo and Ida*, 2002]. Perhaps the solar system simply formed from a lower mass disk than most of the super-Earth systems.

We can qualitatively test this idea using planets observed around different types of stars, because the disk mass is thought to scale (to some degree) with the stellar mass ([e.g., *Williams and Cieza*, 2011]; see discussion in *Raymond et al.* [2007]). Indeed, *Mulders et al.* [2015] found that the population of super-Earths orbiting M stars is statistically different from that orbiting FGK stars. As expected from our simple arguments, M stars host more small super-Earths that are fewer large ones compared with FGK stars (with the division between "small" and "large" set at 2.8 $R_\oplus$). However, the M stars' super-Earths are still easily massive enough to have migrated.

If even M stars' low-mass disks produce super-Earths, then some other factor is needed to explain the inner solar system's very small embryos. Jupiter may be the key. Terrestrial embryos grew from pebbles that drifted inward through the disk, and the source of pebbles moved outward in time [*Lambrechts and Johansen*, 2014; *Morbidelli et al.*, 2015]. When Jupiter's core reached ~20 $M_\oplus$ it became a barrier to the inward flux of pebbles. This starved the terrestrial embryos, leaving them too small to migrate. If the disk had been more massive then the terrestrial embryos could have reached the migration mass faster. And in a low-mass disk without a Jupiter, the inward sweeping of the snow line could have delivered more material to the terrestrial embryos as the disk evolved [*Morbidelli et al.*, 2016].

By these arguments, a system would need two conditions to be met to avoid forming migrating embryos. First, the disk mass must be below a certain threshold to avoid forming migrating terrestrial embryos very quickly. Second, a gas giant must form exterior to the terrestrial zone early enough to block the pebble flux and starve the inner embryos. Of course, these conditions are linked because giant planet cores are also migrating embryos, and cores that end up at ∼5 AU may plausibly originate across the entire disk [*Bitsch et al.*, 2015b; *Raymond et al.*, 2016].

Observations remain difficult to interpret. By combining radial velocity and transit data, bulk density measurements have been made for roughly 100 super-Earths [see *Marcy et al.*, 2014]. Most planets larger than 1.5–2 $R_\oplus$ have low measured bulk densities and may thus be "mini-Neptunes" rather than "super-Earths" [*Weiss and Marcy*, 2014; *Lopez and Fortney*, 2014; *Rogers*, 2015; *Wolfgang and Lopez*, 2015]. Most planets smaller than ∼1.5 $R_\oplus$ have bulk densities expected of rocky planets ([*Dressing et al.*, 2015], but exceptions exist—e.g., *Jontof-Hutter et al.* [2014]). Of course, given the significant error bars and the uncertainty in planetary building materials, the detailed compositions of even the best measured super-Earths remain poorly constrained [e.g., *Adams et al.*, 2008].

The meaning of the transition between super-Earths and mini-Neptunes at $R \approx 1.5\,R_\oplus$ ($M \approx 5-6\,M_\oplus$) remains unclear. This is unlikely to mark the transition between migrating and nonmigrating embryos because there is no clear correlation between orbital radius and planet size. Perhaps 6 $M_\oplus$ is simply the critical mass above which cores can accrete gas from the disk [see, e.g., *Ikoma et al.*, 2001; *Hubickyj et al.*, 2005]. It is interesting to note that *Izidoro et al.*'s [2015b] simulations to reproduce the ice giants were by far the most successful if the icy building blocks were ∼6 $M_\oplus$ in mass. Or perhaps this transition is related to the mass above which atmospheres are more easily retained during the late stage of giant impacts [e.g., *Lee et al.*, 2014; *Inamdar and Schlichting*, 2015, 2016]. This remains an active area of research.

We still have not addressed the question of why there are no super-Earths in the solar system. Indeed, the absence of terrestrial planets interior to Mercury remains a mystery in itself. This absence—as well as Mars' small mass—can be explained if the initial distribution of embryos in the solar system only extended from roughly 0.7 to 1 AU [*Hansen*, 2009]. While significant work has been devoted to understanding the origin of the mass depletion beyond 1 AU, relatively few studies have addressed the very inner solar system.

The absence of super-Earths can be explained relatively naturally by the migration model. Imagine that the first large planetary embryo that formed migrated to a zero-torque location and grew into Jupiter [*Cossou et al.*, 2014], carving a radial gap in the disk. The inward migration of more distant embryos was then blocked by Jupiter [*Izidoro et al.*, 2015a]. Uranus and Neptune, and even Saturn's core, may thus have been trapped in the outer solar system by Jupiter, whereas in the absence of Jupiter these planets or their precursors might have continued to migrate into the inner solar system becoming close-in super-Earths. Simulations of this process are indeed the first to successfully reproduce the relative masses of the ice giants [*Izidoro et al.*, 2015b]. What remains unclear are the conditions required for the first embryo to grow into Jupiter before other embryos can migrate past. Indeed, simulations of the migration model overproduce systems of super-Earths [e.g., *Cossou et al.*, 2014].

Raymond et al. [2016] proposed a hybrid pebble + migration model to explain the absence of terrestrial planets closer-in than Mercury. In their model, Jupiter's core grew quickly in the very inner solar system, presumably by accreting inward drifting pebbles. Following the migration maps of *Bitsch et al.* [2015a], the core subsequently migrated back outward to several astronomical units. During its outward migration, the very inner solar system was swept clean by resonant shepherding [*Tanaka and Ida*, 1999; *Mandell et al.*, 2007]. Simulations show that the sweeping mechanism breaks down at 0.5–1 AU, thus clearing the region interior to Mercury but not the Venus-Earth zone [*Raymond et al.*, 2016]. While provocative, this model is admittedly built on several assumptions (pebble drift and outward migration, notably) with associated uncertainties.

Two recent models have proposed that the primordial solar system contained systems of super-Earths that were later destroyed [*Volk and Gladman*, 2015; *Batygin and Laughlin*, 2015]. However, each of these studies has significant limitations. For instance, *Volk and Gladman* [2015] proposed that the solar system's super-Earths were destabilized and underwent a series of catastrophic collisions that ground the planets to dust.

However, they did not model the actual collisions or collisional grinding, and a cursory examination of the relevant collisional parameters suggests that they were not in the supercatastrophic regime [see *Genda et al.*, 2012; *Leinhardt and Stewart*, 2012]. *Batygin and Laughlin* [2015] proposed that the inward-then-outward migration proposed by the Grand Tack model [*Walsh et al.*, 2011; *Pierens and Raymond*, 2011] produced a giant pulse of collisional debris that drifted inward and pushed a set of super-Earths onto the Sun. However, Batygin and Laughlin (a) did not consistently treat the accretion of collisional debris in the Earth-Venus zone, (b) did not take collisional evolution/growth into account as the debris drifted inward, and (c) ignored the fact that disks have inner edges which are inferred from observations [e.g., *Eisner et al.*, 2005] and naturally produced in models of gas accretion onto stars [e.g., *Romanova et al.*, 2013]. Taking these limitations into account, we do not find either of these studies convincing. (For a more detailed critique of these studies we refer the reader to section 3.1 of *Raymond et al.* [2016].) Yet while the proposed mechanisms are not compelling, it remains a possibility that the solar system once contained a system of super-Earths. What is missing is a viable destruction mechanism and, ideally, an observational signature.

7. Discussion: Is the Solar System Special?

Just like any individual person, the solar system has its own history. The probability of any other planetary system following an identical blueprint is zero. But how typical was the solar system's evolutionary path? (*Did it go to college, get married and get a normal job?*) Or was the solar system's path unusual in some way? (*Did it quit high school to teach scuba diving in Belize?*)

Jupiter is the only solar system planet within the reach of current observations. Based on statistically sound exoplanet observational surveys, the Sun-Jupiter system is special at roughly the level of one in a thousand. First, the Sun is an unusually massive star; the most common type of star are M dwarfs, with masses of 10–50% of the Sun's. The Sun is unusual at the ~10% level, depending on the definition of "Sun-like" and the assumed stellar initial mass function. Second, only ~10% of Sun-like stars have gas giant planets with orbits shorter than a few to 10 AU [*Cumming et al.*, 2008; *Mayor et al.*, 2011]. Third, only about 10% of giant exoplanets have orbits wider than 1 AU and eccentricities smaller than 0.1. The median eccentricity is ~0.25 [*Butler et al.*, 2006; *Udry and Santos*, 2007]. Taken together, these constraints suggest that the Sun-Jupiter system is a 0.1% case. Of course, the situation is more complex than described here, as there exist correlations between a number of relevant parameters such as between the stellar mass and the presence of gas giants [*Johnson et al.*, 2007; *Lovis and Mayor*, 2007] and between the orbital radius and eccentricity [e.g., *Butler et al.*, 2006; *Ford and Rasio*, 2008]. The numbers quoted here are a simple order of magnitude, but they clearly illustrate that the solar system is not a typical case in at least one regard: the presence and orbit of Jupiter.

Currently favored theoretical modeling likewise favors Jupiter as the key player in the solar system's evolution. The Grand Tack model invokes a two-phase migration history for Jupiter [*Walsh et al.*, 2011]. *Izidoro et al.* [2015a] proposed that Jupiter held back the inward migration of Uranus and Neptune and stopped them from become hot super-Earths. Assorted other models invoke Jupiter's growth [*Turrini et al.*, 2012], dynamics [*Izidoro et al.*, 2016], or migration [*Batygin and Laughlin*, 2015] to explain the properties of the solar system.

There remain considerable uncertainties at each step of planet formation. That is the theme of this review: even our most successful models are built on a shaky foundation. Looking to the future, the most important steps forward may be those that show how planet do *not* form.

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