ON THE FORMATION OF SUPER-EARTHS WITH IMPLICATIONS FOR THE SOLAR SYSTEM

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ABSTRACT
We first consider how the level of turbulence in a protoplanetary disk affects the formation locations for the observed close-in super-Earths in exosolar systems. We find that a protoplanetary disk that includes a dead zone (a region of low turbulence) has substantially more material in the inner parts of the disk, possibly allowing for in situ formation. For the dead zone to last the entire lifetime of the disk requires the active layer surface density to be sufficiently small, $\Sigma_{\text{crit}} \lesssim 100 \, \text{g cm}^{-2}$. Migration through a dead zone may be very slow and thus super-Earth formation followed by migration toward the star through the dead zone is less likely. For fully turbulent disks, there is not enough material for in situ formation. However, in this case, super-Earths can form farther out in the disk and migrate inward on a reasonable timescale. We suggest that both of these formation mechanisms operate in different planetary systems. This can help to explain the observed large range in densities of super-Earths because the formation location determines the composition. Furthermore, we speculate that super-Earths could have formed in the inner parts of our solar system and cleared the material in the region inside of Mercury’s orbit. The super-Earths could migrate through the gas disk and fall into the Sun if the disk was sufficiently cool during the final gas disk accretion process. While it is definitely possible to meet all of these requirements, we don’t expect them to occur in all systems, which may explain why the solar system is somewhat special in its lack of super-Earths.

Key words: accretion, accretion disks – planet–disk interactions – planets and satellites: formation – protoplanetary disks

1. INTRODUCTION
We recently identified the two most unusual aspects of our solar system (compared with all of the observed exoplanetary systems): (1) the lack of super-Earths (planets with a mass in the range 1–10 $M_{\oplus}$, e.g., Valencia et al. 2007) and (2) the lack of planets inside of Mercury’s orbit (Martin & Livio 2015). More than half of the observed Sun-like stars in the solar neighborhood have one or more super-Earth planets on low eccentricity orbits with periods of days to months (Mayor et al. 2011; Batalha et al. 2013; Fressin et al. 2013; Burke et al. 2015). This is in contrast to our solar system, which is depleted in mass in this region. To examine potential reasons for this difference, in this work we consider formation processes for super-Earths and investigate the conditions in the solar nebula that could have affected the outcome for our solar system.

The timeline for the formation of the planets in our solar system is thought to have been as follows. The planetesimals formed within a few million years of the birth of the Sun (Connelly et al. 2012). The giant planets formed quickly allowing for the accretion of material from the gas disk (e.g., Alibert et al. 2005). However, the terrestrial planets formed long after the gas disk was dispersed on a timescale of around 10–100 million years (e.g., Kenyon & Bromley 2006). There are no super-Earths in our solar system, so understanding their formation on the basis of solar system data alone is more difficult.

The observed close-in super-Earths exhibit a wide range of densities (e.g., Wolfgang & Laughlin 2012; Howe et al. 2014; Knutson et al. 2014; Marcy et al. 2014a), suggesting that there may be several different mechanisms for their formation (see also Figure 5 in Martin & Livio 2015). In Figure 1 we show the planet mass and semimajor axis of observed exoplanets that have a density measurement (the data are taken from exoplanets.org, Han et al. 2014). The largest points show the low-density planets (planets with densities similar to the giant planets in our solar system, density $\rho < 1.6 \, \text{g cm}^{-3}$), the medium-size points have a density in the range $1.6 \, \text{g cm}^{-3} < \rho < 3.9 \, \text{g cm}^{-3}$, and the small points show the high-density planets (with density greater than $3.9 \, \text{g cm}^{-3}$, similar to the terrestrial planets in our solar system). There appears to be little correlation between the density and the planet mass.1 There is a slight correlation between the density and the semimajor axis in that there are fewer low-density planets close to the star. The compositions of extrasolar super-Earths suggest that at least some of them have substantial gaseous atmospheres. This is at odds with the timescale for terrestrial planet formation and therefore (at least some) super-Earths likely formed while the gas disk was still present. The composition of the planets is dependent on their formation location. Planets that form outside of the water snow line (the radial location from the star where the temperature is low enough for water to become solid, e.g., Lecar et al. 2006; Martin & Livio 2012, 2013) will be water-rich, while those that form close to their star will likely be rockier. We expect that planets that form farther out in the disk may be less dense than those that form close to the star. However, accretion of gaseous material from the disk may significantly reduce the final average density of the planet, and thus the time of planet formation is also important.

There are two general orbital locations suggested for the formation of super-Earths. Either they formed in situ with no significant migration or else they formed similarly to giant planets, outside the snow line in the protoplanetary disk and then migrated inwards. Giant planets with short orbital periods are thought to have formed farther out and migrated inward to

1 There is much discussion on this point in the literature (see e.g., Petigura et al. 2015; Lopez & Fortney 2014; Marcy et al. 2014b; Morton & Swift 2014; Weiss & Marcy 2014).
Hansen & Murray (2012) used $n$-body simulations to form super-Earth planets in situ. They found it was possible if the amount of rocky material interior to 1 au is about 50–100 $M_\oplus$. They suggested that this would require significant radial migration of solid material before the end stages of planet formation. The minimum-mass solar nebular (Weidenschilling 1977; Hayashi 1981) has only 3.3 $M_\oplus$ in solids interior to 1 au, although the planet formation process is not likely to be completely efficient. The ratio of dust to gas is often quoted to be 0.01 in the ISM. However, in accretion disks, observations indicate that it may be much higher (e.g., Williams et al. 2014). The mass in the gas disk in this region would need to be in the range 0.0015–0.03 $M_\odot$. An advantage of the in situ formation model is that it can explain several properties of the observed planet inclination and eccentricity distributions as well as the orbital spacing (Hansen & Murray 2012, 2013).

The alternative super-Earth formation theory suggests that they form farther out in the disk where there is more solid material and then migrate inward (Terquem & Papaloizou 2007; McNeil & Nelson 2009; Ida & Lin 2010; Cossou et al. 2014). In this scenario, planets grow through Earth size embryo–embryo collisions. Smooth migration means that the planets form in chains of mean motion resonances. However, multi-planet systems observed with Kepler generally do not show planets locked into resonances (e.g., Fabrycky et al. 2012; Batygin & Morbidelli 2013; Steffen & Hwang 2015), and thus the resonances must be broken after planet formation (e.g., Rein 2012; Goldreich & Schlichting 2014). Cossou et al. (2014) suggested that hot super-Earths and giant planet cores form in the same way. They both migrate inwards but the giant planet cores become massive enough for the direction of the migration to reverse. The super-Earths pile up at the inner edge of the disk.

In this work we present a gas disk model that allows for the formation via both mechanisms in both locations depending upon the disk properties. In Sections 2 and 3 we construct numerical models of protoplanetary disks without and with a dead zone (a region of low turbulence). This will allow us to draw some conclusions about the formation mechanisms for super-Earths. In Section 4 we discuss the implications for our own solar system and we discuss and summarize our results in Sections 5 and 6.

### 2. FULLY TURBULENT DISK MODEL

In this section we consider the evolution of a fully turbulent protoplanetary gas disk. The disk is in Keplerian rotation with angular velocity $\Omega = \sqrt{GM/R^3}$ around a central mass $M$ at radial distance $R$. Turbulence, driven by the magneto-rotational instability (MRI), drives a kinematic turbulent viscosity

$$\nu = \alpha \frac{c_s}{\Omega},$$

where $\alpha$ is the Shakura & Sunyaev (1973) viscosity parameter, the sound speed is $c_s = \sqrt{R \epsilon / \mu}$ with midplane temperature $\epsilon_c$, $R = 8.31 \times 10^7$ erg K$^{-1}$ mol$^{-1}$ is the gas constant and $\mu = 2.3$ g mol$^{-1}$ is the mean molecular weight. The evolution of the surface density, $\Sigma$, is governed by

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R} \frac{\partial}{\partial R} \left[ R^2 \frac{\partial}{\partial R} (\Sigma R^2) \right],$$

**Figure 1.** Planet mass and semimajor axis of the observed exoplanets with a mass in the range $1 M_\oplus < M_p < 15 M_\oplus$ that have a density measurement. The large blue points denote planets with a low density $\rho \leq 1.6$ g cm$^{-3}$, the medium-size magenta points denote those with a density in the range $1.6$ g cm$^{-3} < \rho < 3.9$ g cm$^{-3}$, and the small red points denote those with a high density, $\rho > 3.9$ g cm$^{-3}$. For reference, in our solar system the terrestrial planets have average densities $\rho > 3.9$ g cm$^{-3}$ and the giant planets have average densities $\rho < 1.6$ g cm$^{-3}$. The data are from exoplanets.org.
(e.g., Lynden-Bell & Pringle 1974; Pringle 1981) where \( \xi = \nu \Sigma \) in this fully MRI turbulent disk.

The temperature evolves according to the simplified energy equation

\[
\frac{\partial T}{\partial t} = \frac{2(Q_+ - Q_-)}{c_p \Sigma} 
\]  

(Pringle et al. 1986; Cannizzo 1993). The disk specific heat for temperatures around \( 10^3 \) K is \( c_p = 2.7 R / \mu \). The disk is heated by viscous dissipation according to

\[
Q_+ = \frac{9}{8} \Omega^2 \xi. 
\]

We assume that each annulus of the disk radiates as a blackbody and so the local cooling is

\[
Q_- = \sigma T_e^4, 
\]

where \( T_e \) is the temperature at the surface of the disk and \( \sigma \) is the Stefan–Boltzmann constant. Assuming energy balance, the mid-plane temperature and the surface temperature are related through

\[
T_e^4 = \frac{3}{4} \tau T_s^4, 
\]

where the optical depth is

\[
\tau = \kappa(T_e) \Sigma \frac{\Sigma}{2}. 
\]

We use the simplified opacity of Armitage et al. (2001) \( \kappa(T) = 0.02 T^{0.8} \) cm\(^2\) g\(^{-1}\) that is valid in the inner parts of the disk.

At early times in the protostellar accretion history the infall accretion rate on to the disk is expected to be around \( M_{\text{infall}} \approx c_s^2 / G \) (e.g., Larson 1969; Shu 1977; Basu 1998). For temperatures around \( 10^3 \) K, the infall accretion rate is of the order of \( 10^{-5} M_\odot \) yr\(^{-1}\). We first run a disk model with a constant infall accretion rate of \( 1 \times 10^{-5} M_\odot \) yr\(^{-1}\) until it reaches a steady state. This is the initial disk setup that we use for all of the simulations. The infall accretion rate on to the disk evolves with time as

\[
M_{\text{infall}} = \dot{M}_i \exp \left( -\frac{t}{t_{\text{ff}}} \right),
\]

where the initial accretion rate is \( 10^{-5} M_\odot \) yr\(^{-1}\) and \( t_{\text{ff}} = 10^5 \) year (see Armitage et al. 2001; Martin et al. 2012b).

2.1. In Situ Super-Earth Formation

We integrate the disk evolution Equations (4) and (5) for a disk that extends from \( R_{\text{in}} = 2.33 \times 10^3 \) au to \( R_{\text{out}} = 40 \) au around a solar mass star. The grid contains 200 points distributed uniformly in \( R^2 \). Material is added to the disk at a radius of 35 au. At the inner edge of the disk a zero torque boundary condition allows the inward flow of gas out of the grid and toward the central star. The flow is prevented from leaving the outer boundary with a zero radial velocity outer boundary condition.

We consider a fully turbulent disk model that has a viscosity parameter \( \alpha = 0.01 \) everywhere in the disk (e.g., Hartmann et al. 1998). Figure 2 shows the mass of the disk inside of \( R = 1 \) au (lower line) and the total disk mass up to \( R = 40 \) au (upper line) as a function of time. The material in \( R < 1 \) au is potentially available for the formation of super-Earth planets in these inner regions. Note that the amount of mass in the MMSN in this region is \( 0.002 M_\odot \). It seems a little surprising that the fully turbulent disk model is never above this value. This is partially because the MMSN is not applicable inside of Mercury’s orbit. The MMSN has a very steep dependence on radius and thus predicts a rather high mass in the inner regions of the disk. Similarly, the MMEN also predicts a very high mass in the inner regions in order to be able to form the observed exoplanets. We can conclude that the fully turbulent disk model probably cannot form the planets that are observed close to their host stars in situ.

2.2. Migration of Super-Earths

While in situ formation of super-Earths seems to be ruled out in the case of a fully turbulent disk, formation of super-Earths farther out in the disk followed by inward migration remains a possibility in the fully turbulent disk model. There are two types of planetary migrations depending on the mass of the planet and the properties of the disk. In type I migration, the planet is not massive enough to open a gap in the disk and the surface density of the disk remains largely unperturbed by the presence of the planet. This type of migration is not dependent on the viscosity of the disk. In a fully turbulent disk, super-Earths are not large enough to open a gap in the disk and so they migrate via type I migration. The timescale for this migration is given approximately by

\[
\tau_{\text{type I}} \approx 6.7 \times 10^5 \left( \frac{M_p}{5 M_\oplus} \right)^{-1} \left( \frac{M}{1 M_\odot} \right)^{-1} \left( \frac{a}{1 \text{ au}} \right)^{-\frac{1}{2}} \times \left( \frac{\Sigma}{100 \text{ g cm}^{-2}} \right)^{-1} \left( \frac{H/R}{0.05} \right)^2 \text{ year} 
\]  

Figure 2. Disk mass up to a radius of \( R = 1 \) au as a function of time (the lower line) and total disk mass up to a radius of 40 au (upper line). The initial disk surface density is a steady-state fully turbulent disk with an infall accretion rate of \( 1 \times 10^{-5} M_\odot \) yr\(^{-1}\). The infall accretion rate decreases exponentially in time according to Equation (10). The dashed lines show the mass in \( R < 1 \) au for the MMSN (lower) and the MMEN (upper).
include thermal ionization, cosmic ray ionization, and the effects of recombination.

Because the dead zone acts like a plug in the accretion flow, material accumulates in this region and may become massive enough to become self-gravitating. Viscosity may be generated by the MRI and by self-gravity (Paczynski 1978; Lodato & Rice 2004). The viscosity driven by the MRI in the magnetic layers is

\[ \nu_m = \alpha_m \frac{c_m^2}{\Omega}, \]

where we take \( \alpha_m = 0.01 \) and \( c_m = \sqrt{RT_m/\mu} \) is the sound speed in the magnetic layer with temperature \( T_m \). The dead zone is assumed to have zero turbulence unless it becomes self-gravitating. However, the inclusion of a small amount of turbulence in the dead zone (e.g., \( \alpha \lesssim 10^{-3} \)) does not affect the behavior of the disk significantly (Martin & Lubow 2014). As material builds up, the disk becomes self-gravitating if the Toomre parameter \( Q < Q_{\text{crit}} = 2 \), where

\[ Q = \frac{c_g \Omega}{\pi G \Sigma}, \]

(Toomre 1964) and the sound speed at the disk mid-plane is given by \( c_g = \sqrt{RT/\mu} \). We approximate the temperature of the self-gravitating region as the mid-plane temperature, \( T_c \). Self-gravity drives a viscosity that is approximated by

\[ \nu_g = \alpha_g c_g^2 \left( \frac{\epsilon T_{\text{crit}}^4}{Q_{\text{crit}}} \right)^2 - 1 \]

for \( Q < Q_{\text{crit}} \) and zero otherwise (e.g., Lin & Pringle 1987, 1990) and we take \( \alpha_g = \alpha_m \).

The surface density and temperature evolution for a disk with a dead zone is given by Equations (4) and (5), but here with \( \xi = \nu_m \Sigma_m + \nu_g \Sigma_g \). The magnetic layer temperature is related to the surface temperature with

\[ T_m^4 = \frac{3}{4} \tau_m T_c^4, \]

where the optical depth to the magnetic region is

\[ \tau_m = \kappa(T_m) \frac{\Sigma_m}{2}. \]

The optical depth within the dead zone layer is

\[ \tau_g = \kappa(T_c) \frac{\Sigma_g}{2} \]

and

\[ \tau = \tau_m + \tau_g. \]

The cooling function is found to be

\[ Q_c = \sigma T_c^4 = \tau^{-1} \left( \sigma T_c^4 + \frac{9}{8} \Omega^2 \nu_m \Sigma_m \right) \]

(Martin & Lubow 2011). Although the disk is not in thermal equilibrium, we apply this cooling function to Equation (5) and so we do not attempt to treat the cooling during viscosity transitions consistently.

The initial disk setup is the steady-state disk with an infall accretion rate of \( 10^{-5} M_\odot \text{yr}^{-1} \). The infall accretion rate

(\( \tanaka et al. 2002; \) Armitage 2013), where \( M_p \) is the mass of the planet, \( a \) is the orbital radius of the planet, \( M \) is the mass of the star, and \( H/R \) is the disk aspect ratio. We do note that this timescale is very sensitive to disk parameters and the direction of type I migration is determined by the mass of the planet.

Equation (11) shows that the inward migration timescale is around a few \( 10^5 \) year and so the migration can comfortably take place within the lifetime of the disk. The difficulty is rather how to stop the migration (e.g., Ida & Lin 2008). There has been much discussion about planet traps that change the direction of type I migration (e.g., Masset et al. 2006; Morbidelli et al. 2008; Hasegawa & Pudritz 2011, 2013). These can occur at transitions such as snow lines, dead zone boundaries, and heat transitions. The radial location of such a trap may move slowly in time, thus transporting the planet on a much longer timescale. Thus, formation farther out followed by inward migration is possible in principle in the fully turbulent disk model.

3. DISK MODEL WITH A DEAD ZONE

It is generally accepted that protoplanetary disks are not fully turbulent, but rather that they contain a region of low turbulence, a dead zone (e.g., Gammie & Menou 1998; Turner & Sano 2008; Bai 2011; Okuzumi & Hirose 2011; Simon et al. 2011; Dryer & et al. 2013). We therefore solve the accretion disk equations that include a dead zone region. We define \( \Sigma_m \) to be the surface density in the MRI active layers and

\[ \Sigma_g = \Sigma - \Sigma_m \]

is the surface density in the dead zone layer. If there is no dead zone at a particular radius, then \( \Sigma_g = 0 \) and \( \Sigma_m = \Sigma \) there. We consider two prescriptions for determining the surface density of the dead zone.

1. We assume that the disk surface layers are ionized by external sources (cosmic rays or X-rays from the central star, e.g., Sano et al. 2000; Matsumura & Pudritz 2003; Glassgold et al. 2004) to a maximum surface density depth of \( \Sigma_{\text{crit}}(T) \) on the upper and lower disk surfaces, where \( \Sigma_{\text{crit}} \) is constant (e.g., Armitage et al. 2001; Zhu et al. 2010a; Martin & Lubow 2011). Cosmic rays are thought to ionize about 200 g cm\(^{-2}\), while X-rays are about an order of magnitude smaller. The disk surface layers always contain MRI turbulence. Furthermore, if the temperature is greater than a critical value, \( T_{\text{crit}} \), then the disk is thermally ionized allowing the MRI to operate throughout the vertical extent. The value of \( T_{\text{crit}} \) is not well-determined and so we consider two values of 800 and 1400 K (e.g., Armitage et al. 2001; Zhu et al. 2010b). Thus, the disk is MRI active if either \( T_c > T_{\text{crit}} \) or if \( \Sigma < \Sigma_{\text{crit}} \) and otherwise there is a dead zone layer at the mid-plane.

2. The dead zone surface density is determined via a critical magnetic Reynolds number (e.g., Hawley et al. 1995; Fleming et al. 2000; Martin et al. 2012a, 2012b). The disk is “dead” if \( R_{\text{M}} < R_{\text{M, crit}} \), where \( R_{\text{M}} = \sqrt{\alpha c_s H/\eta} \), where \( H \) is the disk scale height and the Ohmic resistivity is \( \eta = 234 \tau_{\text{c}} T_c/x_e \text{ cm}^2 \text{ s}^{-1} \) (Blaes & Balbus 1994) and \( x_e \) is the electron fraction. We use the analytic approximations for the active layer surface density shown in Equations (27) and (28) in Martin et al. (2012a) that
decreases exponentially in time according to Equation (10). Thus, the total amount of mass that is accreted on to the disk is exactly the same in these disk models as in the fully turbulent disk model described in the previous section. The disk with a dead zone is not in a quasi-steady-state as the infall accretion rate decreases, as the fully turbulent disk model is. Instead, material building up becomes self-gravitating. The extra heating by self-gravity can lead to the MRI being triggered within this region if the infall accretion rate is sufficiently high. When this happens, the disk becomes MRI active throughout, leading to a large amount of material accreting on to the star in a short time interval (Martin & Lubow 2013). This is an accretion outburst that is thought to be the explanation for the observed FU Orionis-type outbursts (e.g., Armitage et al. 2001; Zhu et al. 2010a; Martin & Lubow 2011). These outbursts occur during the initial disk evolution; at later times when the infall accretion rate has dropped there may still be a dead zone, but there are no further outbursts. Planets that survive must form after the last outburst otherwise they will likely be swept on to the central star during the outburst.

3.1. In Situ Super-Earth Formation

We first consider the possibility of in situ super-Earth formation by examining the amount of material in the inner parts of the disk available for planet formation. We consider a dead zone defined by model 1 with \( T_{\text{crit}} = 800 \, \text{K} \) and \( \Sigma_{\text{crit}} = 200 \, \text{g cm}^{-2} \). Figure 3 shows the evolution of the amount of material at \( R < 1 \, \text{au} \). The sharp increases in the amount of material are when an outburst is triggered and a large amount of material flows through the region. We suggest that if super-Earths are to form and survive within such a disk, they must form after the last accretion outburst. For this model, the dead zone is accreted and the disk becomes fully turbulent at a time of around \( 10^5 \, \text{yr} \). The disk lifetime of the disk is somewhat high, around \( 0.1 \, M_\odot \) at \( t = 10 \, \text{Myr} \). Observations of disk masses are typically derived from measuring the amount of dust. Assuming a gas to dust ratio of 100, observed masses are in the range \( 10^{-3} - 0.1 \, M_\odot \) (e.g., Williams & Cieza 2011). Thus, the disk masses predicted by this model are on the high side. However, in a disk with a quiescent dead zone, the dust will concentrate to the midplane and therefore observations may underestimate the mass of the gas disk. The process of photoevaporation depends upon the accretion flow changing from being dominated by viscous torques to being dominated by the wind mass loss. This transition occurs once the accretion flow through the disk reaches a critical value that is typically in the range of \( 10^{-10} - 10^{-8} \, M_\odot \, \text{yr}^{-1} \) depending upon the dominant photon flux, X-rays, EUV, or FUV (e.g., Alexander et al. 2000; Owen et al. 2011). Photoevaporation of the outer parts of the disk will cut off the supply of material to the inner parts. The final accretion outburst shown in the model will most likely not take place and super-Earths that form while the disk mass is high will survive.

Figure 3. Same as Figure 2 except the disk has a dead zone defined by model 1 with \( \Sigma_{\text{crit}} = 200 \, \text{g cm}^{-2} \) and \( T_{\text{crit}} = 800 \, \text{K} \).

Figure 4. Same as Figure 2, except the disk has a dead zone defined by model 1 with \( \Sigma_{\text{crit}} = 20 \, \text{g cm}^{-2} \) and \( T_{\text{crit}} = 800 \, \text{K} \).
et al. 2014). In our model most of the disk mass (97%) is in the dead zone at the end of the simulation and so the accretion flow rate through the disk is small. While the total disk mass may be high, the viscous accretion rate is low, and therefore photoevaporation should be able to efficiently clear the disk.

Figure 5 shows a disk with a dead zone defined by model 1 with $\Sigma_{\text{crit}} = 20 \text{ g cm}^{-2}$ and $T_{\text{crit}} = 1400 \text{ K}$. The higher critical temperature allows more time for super-Earth formation at earlier times. Again, we suggest that the final outburst shown will not take place because the disk will be photoevaporated before this time.

Figure 6 shows a disk with a dead zone determined by model 2. The critical magnetic Reynolds number is $R_{\text{M, crit}} = 5 \times 10^4$. For this model the active layer surface density changes with radius. The inner parts of the disk are almost entirely non-turbulent and a significant amount of material builds up there. There is more than enough material for super-Earths to form in situ. After a time of about $10^6$ year the disk has more material than the MMEN in $R < 1$ au for the rest of the disk lifetime.

In our disk model, the inner edge of the dead zone is determined by the radial distance at which the temperature of the disk drops below that required for thermal ionization. It does not change in time because the temperature profile is not significantly affected by a dead zone (see for example Lubow & Martin 2013) unless it becomes self-gravitating.

In conclusion, we have shown that the disk mass inside of 1 au may be several times that of the MMEN for the later stages of the disk life and thus formation of super-Earths in this region is possible, depending on the dead zone parameters. We should note that we have described only a representative sample of the results obtained from a series of simulations. From all the simulations we find that the dead zone persists long enough for the formation of super-Earths provided that $\Sigma_{\text{crit}} \lesssim 100 \text{ g cm}^{-2}$. While the value of the active layer surface density is still somewhat uncertain, this value may be representative of protoplanetary disks. Still, since different protoplanetary disks may have different values, super-Earths may form in situ in some systems but not in others.

3.2. Migration of Super-Earths

Formation of super-Earths farther out in the disk with subsequent inward migration may be more difficult in a disk with a dead zone. While the rate of type I migration is not affected by viscosity (or the presence of a dead zone), the low viscosity means that the planet more likely migrates by type II migration (e.g., Matsumura & Pudritz 2005, 2006). Traditionally it was thought that there are two gap-opening criteria that need to be satisfied in order for a planet to open a gap in the disk. The first is the viscous gap-opening criterion

$$\frac{M_p}{M} \gtrsim \left( \frac{40\nu}{R^2\Omega} \right)^2 \left( \frac{H}{R} \right)^3 = \frac{\left( \frac{H}{R} \right)^5}{(40\alpha)^2} \left( \frac{H}{R} \right)^5$$

(Lin & Papaloizou 1986). Lin et al. (1993) suggested that a second criterion, the thermal criterion, must also be satisfied for a planet to open a gap. That is, the Hill radius of the planet must be larger than the disk scale height. However, more recently it has been found that this criterion is too strong (e.g., Rafikov 2002). Zhu et al. (2013) find that due to the nonlinear wave steepening, a low-mass planet can open a gap in contradiction to the thermal criterion. In this work we assume that the gap-opening criterion is determined by the viscous torque on the disk balancing the tidal torque from the planet. Rearranging Equation (21), we find that a super-Earth can open a gap in the disk provided that the viscosity parameter satisfies

$$\alpha \lesssim 1.8 \times 10^{-5} \left( \frac{M_p}{5 M_\oplus} \right)^2 \left( \frac{M}{1 M_\oplus} \right)^{-2} \left( \frac{H}{R} \right)^{-5} \left( \frac{0.05}{0.05} \right).$$

That is, the dead zone does not have to be entirely turbulence-free for a super-Earth to open a gap.
Type II migration typically proceeds on the viscous timescale for the disk

$$\tau_v = \frac{R^2}{\nu} = \frac{1}{\alpha (H/R)^2 \Omega}$$

(e.g., Pringle 1981). For typical parameters this is given by

$$\tau_v = 7.1 \times 10^4 \left(\frac{\alpha}{0.01}\right)^{-1} \left(\frac{H/R}{0.05}\right)^2 \left(\frac{M}{1 M_\odot}\right)^{-\frac{3}{2}} \left(\frac{R}{5 \text{ au}}\right)^{\frac{3}{2}} \text{ year.}$$

This can be longer than the lifetime of the disk for $\alpha \lesssim 10^{-4}$. If a super-Earth forms inside a dead zone, it may be trapped there in the dead region, while migrating only very slowly by type II migration.

The disk becomes depleted in time because the infall accretion rate declines while material continues to accrete on to the star through the active surface layers. Concomitantly, the dead zone size gradually decreases. In the end stages of the disk’s life, the disk becomes fully turbulent down to the mid-plane (this occurs when $\Sigma \lesssim \Sigma_{\text{crit}}$ everywhere that $T < T_{\text{crit}}$) and the inner parts of the disk accrete on to the star. When the disk becomes turbulent, the planet may no longer be able to hold a gap open, and type I migration may occur. We discuss this possibility further in the next section.

4. SUPER-EARThS IN THE EARLY SOLAR SYSTEM

The lack of super-Earths in our solar system sets us somewhat apart from observed exoplanetary systems. There are two possible explanations for this dearth of super-Earths. Either conditions in the solar nebula did not allow for the formation of super-Earths, or else they did form but were subsequently somehow removed. Given that the orbits of the planets in the solar system are coplanar and not very eccentric, planet–planet scattering does not seem to be a likely ejection mechanism. Thus, if super-Earths formed, they most likely fell into the Sun.

If super-Earths form outside of the snow line and migrate inward through a gas disk, they affect the composition of the terrestrial planets if they migrate slowly enough (Izidoro et al. 2014). Therefore, if they formed in our solar system, they would have had to migrate quickly, on a timescale of about $0.01$–$0.1$ Myr. If the timescale is longer than this, then a super-Earth shepherds rocky material interior to its orbit and depletes the terrestrial planet-forming zone. Terrestrial planets that form may be volatile-rich and are more likely to be water worlds that are not very Earth-like.

Consequently, the most probable formation site in our solar system is in the inner regions, inside of Mercury’s orbit. The lack of any objects in this region may indeed suggest that super-Earths formed close to our Sun, clearing the region of debris, but they subsequently fell into the Sun. The mechanism that pushed the super-Earths into the Sun could be simply migration through the gas disk. At the end of the gas disk’s lifetime, photoevaporation removes the remaining gas on a short timescale (e.g., Clarke et al. 2001; Alexander et al. 2006; Owen et al. 2011). However, this process only operates outside of the gravitational radius from the star, typically around 5–10 au (e.g., Hollenbach et al. 1994). The inner parts of the disk that we are interested in accrete onto the central star on a viscous timescale. The maximum total surface density present in the disk during this process is the critical active layer surface density, $\Sigma_{\text{crit}}$. If the critical active layer’s surface density is small, then the planets will not move far during this process. However, a large critical surface density may be sufficient for a super-Earth to migrate into the Sun. We therefore find that there is a delicate balance between the need for a sufficiently large surface density in the active layer for the planets to migrate into the star, but also a small enough active layer surface density to allow the planets to form in situ in the first place.

For the super-Earth to migrate into the Sun, it must do so on a timescale shorter than the viscous timescale (the timescale for the disk to accrete). Equating Equations (11) and (24) we find that the minimum surface density in the disk for the planet to migrate in to the Sun is

$$\Sigma_{\text{min}} = 940.5 \left(\frac{\alpha}{0.01}\right)^{\frac{1}{4}} \left(\frac{H/R}{0.05}\right)^{\frac{3}{4}} \left(\frac{M}{1 M_\odot}\right)^{\frac{3}{4}} \left(\frac{R}{5 \text{ au}}\right)^{\frac{3}{4}} \left(\frac{M_\odot}{5 M_\odot}\right)^{-1} \text{ g cm}^{-2}.$$  

Now, if $\Sigma_{\text{crit}} > \Sigma_{\text{min}}$, then we expect that super-Earths that form in situ will migrate into the Sun at the end of the disk lifetime. On the other hand, if $\Sigma_{\text{crit}} < \Sigma_{\text{min}}$, then there may be some type I migration but not enough to allow the super-Earth to be accreted. Note that Equation (25) is very sensitive to the disk aspect ratio. For example, if the disk aspect ratio is decreased by a factor of two, down to $H/R = 0.025$, then we find that $\Sigma_{\text{min}} \approx 60$ g cm$^{-2}$. We speculate that in our solar system, super-Earths formed in the inner parts of a relatively cool disk close to the dead zone inner boundary. There was sufficient time for them to migrate through the disk to be accreted on to the Sun. While this outcome is less likely because of the cool conditions required, it is definitely not impossible and should happen in other planetary systems also.

We note that there are alternative mechanisms proposed to explain the lack of super-Earths in the solar system, as well as the absence of planets closer-in than Mercury. Recently, Raymond et al. (2016) suggested that the core of Jupiter may have formed in this region. They invoked the outward migration of Jupiter’s core to its current location to clear out the inner solar system. The lack of super-Earths alternatively could be explained if Jupiter, at its current location, acted as a barrier to the inward migration of outer cores (Izidoro et al. 2015a). In this idea, the building blocks of the ice giants, as well as Saturn’s core, would have become super-Earths if not for Jupiter holding them back (Izidoro et al. 2015b). Finally, an alternative mechanism for pushing close-in super-Earths into the Sun is a variant of the grand tack model. In the grand tack model, Jupiter migrates inwards to 1.5 au before it gets locked into resonance with Saturn and then they both move outwards to their current locations (Walsh et al. 2011). Batygin & Laughlin (2015) suggested that during this process the innermost super-Earths may get shepherded in to the Sun.

5. DISCUSSION

The MMEN is criticized because of the unusually high amount of material required for the in situ formation of super-Earths. However, sub-mm observations of disks measure the properties of the outer disk while the inner parts of the disk are not very well constrained. Furthermore, Ogihara et al. (2015)
suggest that in situ formation cannot operate unless type I migration is suppressed in the region inside of 1 au. A disk model with a dead zone (such as the one proposed in this work) not only provides sufficient material, but it also suppresses the rate of migration in that region.

Raymond & Cossou (2014) argue that super-Earths could not have formed in situ. They use observations of systems that contain three or more planets to construct an MMEN and find that the surface density profile $\Sigma \propto R^{-\sigma}$ has $-3.2 < \sigma < 0.5$. They suggest that because viscous accretion disk models have difficulty in reproducing such extreme profiles that the super-Earths could not have predominantly formed in situ. These conclusions are based on a steady state disk model with the temperature profile dominated by stellar irradiation (e.g., Chiang & Goldreich 1997). However, we suggest that the extreme values could be a result of a discontinuous surface density distribution brought about by the presence of a dead zone. In the dead zone material builds up and the surface density in the innermost MRI active parts of the disk may be significantly lower than that farther out in the dead zone. If this is the case, then one cannot smooth the profile from three planets out to a continuous surface density distribution. Consequently, the most important factor is the amount of material in the inner regions available for planet formation, rather than its distribution.

Because planets that form in situ are expected to require an unusually large amount of solids in the inner parts of the disk, the prediction is that the metallicity of the host star must be higher in such cases. Zhu (2015) found that close-in super-Earths are more likely to be found around metal-rich stars. Similarly, the widely separated super-Earths are more often around metal-poor stars. As metal-rich stars have more solid material closer to the star within the disk, this appears to favor the in situ formation. However, there may be two populations of super-Earths because there is a distinct transition in orbital period observed, rather than a smooth transition.

Chatterjee & Tan (2014) proposed a mechanism to form the close-in super-Earths at the pressure trap at the inner edge of a dead zone, known as inside-out planet formation. Once a planet forms there, the inner edge of the dead zone moves out allowing planet formation further out (Chatterjee & Tan 2015; Hu et al. 2015). This model requires a high rate of supply of pebbles to the inner disk. We suggest that a dead zone model can provide all the required material for planet formation without the need for accumulation. However, the inside-out planet formation mechanism potentially increases the range of possible dead zone parameters that are able to form the super-Earths in situ.

In this work we have considered only the formation of super-Earth planets during the gas disk lifetime. It is entirely possible that some super-Earth planets may form after the gas disk has dissipated and we expect these to have a high density, similar to the terrestrial planets in our solar system. However, this is not the only mechanism to form high density super-Earths. A super-Earth that forms in a dead zone with a small active layer will not accrete much material once it has carved out a gap. The only accretion on to the planet is through the active layer. Thus, planets that form within a dead zone are likely to be less gaseous and more dense than planets that form farther out in a fully turbulent disk and migrate inwards. This may explain the weak dependence of density on semimajor axis observed in Figure 1. However, the gaseous atmosphere of a close-in super-Earth could be stripped from the planet, by tidal evolution or evaporation, leaving only the solid core behind (e.g., Schaefer & Fegley 2009; Jackson et al. 2010). Consequently, as we cannot tell the difference between these two mechanisms in the observed exoplanets, it is difficult to make firm conclusions as to which super-Earths form by which mechanism. Nevertheless, the existence of these different mechanisms may explain the range in the densities.

6. CONCLUSIONS

There are two possible formation locations for observed close-in super-Earths in exoplanetary systems: either in situ or farther away from the star followed by migration to their observed location. We find that a disk that contains a dead zone (a region of low turbulence) may have sufficient material for the planets to form in situ although it depends upon the dead zone parameters. For the dead zone to last long enough for super-Earths to form, the active layer surface density must be sufficiently low, $\Sigma_{\text{crit}} \lesssim 100$ g cm$^{-2}$. If the active layer surface density is too large, the disk becomes fully turbulent before there is sufficient time to form the super-Earths. Migration of super-Earths through a dead zone is very slow and thus formation farther out in a disk with a dead zone is more difficult.

We find that a fully turbulent protoplanetary disk model does not have sufficient material in the inner parts of the disk for in situ formation of super-Earths. In this case, the only possible formation mechanism involves migration from farther out in the disk. The fast rate of migration in a fully turbulent disk lends itself to this scenario. We suggest that the observed large range in super-Earth compositions may be the result of these two very different formation locations.

The lack of super-Earths in our solar system is somewhat puzzling, given that more than half of observed exoplanetary systems contain one. However, the fact that there is nothing inside of Mercury’s orbit may not be a coincidence. In situ formation of super-Earths in that region could have cleared the solid material. The super-Earths would have had to subsequently fall into the Sun. This is possible if the active layer surface density is sufficiently large enough that during the final accretion process there was enough material in the disk for the planets to migrate into the Sun. To satisfy both this constraint and the constraint that the dead zone must last throughout the disk lifetime requires a sufficiently cool disk during the final accretion process. The level of fine-tuning required is certainly possible, but we do not expect it to happen in all systems and this can explain why the solar system is somewhat special in its lack of super-Earths.

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REFERENCES

Alexander, R., Pascucci, I., Andrews, S., Armitage, P., & Cieza, L. 2014, in Protostars and Planets VI, ed. H. Beuther, R. S. Klessen, C. P. Dullemond, & T. Henning (Tuscon, AZ: Univ. Arizona Press), 475
Alexander, R. D., Clarke, C. J., & Pringle, J. E. 2006, MNRAS, 369, 216
Alibert, Y., Mordasini, C., Benz, W., & Winnisdorffer, C. 2005, A&A, 434, 343
Armitage, P. J. 2013, Astrophysics of Planet Formation (Cambridge: Cambridge Univ. Press)
