The circulation of dust in protoplanetary discs and the initial conditions of planet formation

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ABSTRACT

We examine the consequences of a model for the circulation of solids in a protoplanetary nebula in which aerodynamic drag is counterbalanced by the recycling of material to the outer disc by a protostellar outflow or a disc wind. This population of circulating dust eventually becomes unstable to the formation of planetesimals by gravitational instability, and results in the ultimate deposition of \( \sim 30–50 \, M_\oplus \) in planetesimals on scales \( R < 1 \, AU \). Such a model may provide an appropriate justification for the approximately power law initial conditions needed to reproduce observed planetary systems by in situ assembly.

Key words: accretion discs – planets and satellites: formation – protoplanetary discs

1 INTRODUCTION

The detection of planets orbiting other stars has revealed a great diversity of both planetary mass and location, including several populations which have no analogue in our own solar system. Of particular interest is the discovery of substantial numbers of sub-Jovian planets with orbital periods shorter than that of Mercury, using both the radial velocity and transit techniques (Howard et al. 2010; Mayor et al. 2011; Borucki et al. 2011; Borucki et al. 2012). Recently, two groups of authors (Boley & Ford 2013; Chatterjee & Tan 2013) have proposed models that use this idea as the basis for a scenario for inside-out planet formation, in which solid material migrates inward due to drag forces until it stalls due to a pressure maximum, either at the inner edge of the dead zone or near an evaporation or sublimation front. The resulting accumulation of material causes planetesimals to form and to extend the truncation of the disc outwards, resulting in what these authors call ‘Systems with Tightly-packed Inner Planets’, or ‘STIPS’. These proposals may indeed provide compact planetary systems, but they may, in fact, produce systems that are too radially concentrated.

The distribution of known extrasolar planets (Figure 1) shows two distinct length scales for giant planets (an overdensity near 0.05 AU and an increase in frequency \( > 0.7 \, AU \)) but no corresponding special location for planets with mass \( < 0.1 \, M_J \), as might be expected if the pile-up is generated by a feature in the underlying disc structure, such the inner edge of a dead zone. Indeed, attempts to characterise these planetary systems consistently find relatively smooth distributions. Chiang & Laughlin (2013) construct a ‘Minimum Mass Kepler Nebula’ by considering the ensemble properties of the Kepler planet candidate sample, and derive an empirical distribution consistent with an power-law distribution of surface density, \( \Sigma \propto R^{-1.6} \). Hansen & Murray (2012, 2013) suggested that such conditions could be realised if solid material is concentrated radially in the inner parts of the gas disc prior to the late-stage assembly into solid planets. This is not an outrageous expectation as it is well known that small bodies in gas discs are potentially subject to dynamically important aerodynamic drag forces (Whipple 1972; Weidenschilling 1977a; Takeuchi & Lin 2002; Bai & Stone 2010). However, the particular details of how such a model might set the stage for planet formation are still unclear. In this paper we attempt to outline a simple model that provides such a framework.
No such obvious change in planet frequency appears for masses of the physics that determines the planet formation and evolution. Planets appears to change dramatically, a possible indication of the vertical dashed lines indicate two locations where the incidence of giant planets may influence this discussion), as of October 2013. The vertical only (transit detection exhibits a strong selection function that can an unknown inclination angle) detected by radial velocities. The points show the various planetary masses (mod-

![Figure 1](image)

**Figure 1.** The points show the various planetary masses (modulo an unknown inclination angle) detected by radial velocities only (transit detection exhibits a strong selection function that may influence this discussion), as of October 2013. The vertical dashed lines indicate two locations where the incidence of giant planets appears to change dramatically, a possible indication of the physics that determines the planet formation and evolution. No such obvious change in planet frequency appears for masses < 0.1MJ.

2013) recover a very similar underlying model in matching their assembly simulations for these planets to the observations, and found that initial density profiles that were too steep produced planetary systems that were too compact to match the observations.

The inside-out packing of planets in the STIPS models produce a spacing of planets that is dictated by the considerations of dynamical stability of interacting neighbouring planets (Chatterjee & Tan 2013). Monte Carlo models of the in situ assembly of the observed planetary systems (Hansen & Murray 2013) are able to match the observed distributions of periods and period ratios of the observed Kepler systems. However, the resulting distribution in planetary spacings peaks at factors of 2–3 times larger than the threshold for dynamical stability, suggesting that the final configuration is not as tightly packed as it would be if it were assembled sequentially from the inside out.

In this paper, we consider an alternative notion – namely that the solid material is not trapped, but rather migrates rapidly to the inner edge of the protoplanetary disc, from whence it is returned to the outer disc, to begin the inspiral anew. We then examine the consequences of this hypothesis and the manner in which the resulting steady-state distribution of solids can form the initial conditions for the later stages of planetary formation. Such a model finds support within our own Solar System via the evidence for widespread processing at high temperatures in chondrites (e.g. Scott & Krot 2005) and in the observation that the chemical constituents of the comet Wild-2 show evidence of substantial chemical processing in the hotter inner regions of the protosolar nebula (Brownlee et al. 2006; McKeegan et al. 2006; Brownlee, Joswiak & Matrajt 2012).

Indeed, such considerations have long spurred suggestions that material was recirculated in the protosolar nebula (Liffman & Brown 1995; Shu, Shang & Lee 1996; Shu et al. 2001; Hu 2010; Salmeron & Ireland 2012). These models propose that solid material in the inner parts of the protoplanetary nebula are levitated and carried outwards by either the magnetic funnel of the stellar wind or by a magnetically driven outflow from the disk, ultimately to be returned to the protoplanetary nebula on larger scales. Protostellar outflows are a common feature of young stars, and the entrainment of solid material into such ‘winds’ offers a mechanism to redistribute material from the locations near the star to more distant locations. The most prominent of these models is that of Shu et al., which proposes that the chemical processing observed in the constituents of asteroids (at ~ 3 AU from the Sun) may have, in large part, occurred at distances of a few stellar radii, with the material subsequently swept up into the outflow until the material decoupled from the wind and fell back to the disc. One of the principal motivations of this model was to describe the heating and chemical alteration of meteoritic components such as chondrules by processes near the magnetic X-point where the disc and the stellar magnetosphere meet. Recent cosmochemical and age-dating evidence (Connelly et al. 2008; Desch et al. 2012) favor more traditional explanations for these effects, but this does not necessarily invalidate the dynamical component of the X-wind model. An alternative launching mechanism can be found in models where the inner parts of protoplanetary discs are dominated by strong magnetic fields which launch magnetocentrifugal winds (Königl & Pudritz 2000; Bai & Stone 2013; Armitage, Simon & Martin 2013) from a wider range of radii, which may also entrain solid materials and return them to the outer disc.

Our goal is to examine the effect that such a model has on the global inventory of solid material in the protoplanetary disc, and how it might set the stage for subsequent evolution. Thus, in §3 we describe a simple model of an evolving gaseous protoplanetary disc, within which we describe the dynamics of small (dust) particles of various size, which migrate radially inwards until they reach the inner edge of the disc, at which point they are redistributed outwards to begin the cycle again. In §4 we describe the resulting evolution of gas and dust components and how they set a context for planet formation through the onset of gravitational instability and the formation of planetesimals.

### 3 GAS DISK MODEL

In order to describe the dynamics of the solid particles, we need to adopt a model for the evolution of the gaseous protoplanetary disc, which acts as the background for the evolution of the solids. We follow the description of Alexander & Armitage (2007) – hereafter AA07 – which provides a simple model of a protoplanetary disc that includes the viscous evolution as well as the evolution through the transition disc phase and eventual dissipation of the disc.

The gas surface density $\Sigma_g$ evolves according to the tra-
our model.

standard accretion and viscous spreading, but eventually results
from the central star. The inclusion of the
photoionization from the central star. The inclusion of the
amounts to the conservation of the integral of
neglecting the photoevaporation but including an evolution
disc. We incorporate this as an alternative disc model by
leaving an outer disc and an inner hole. The outer disc is
then slowly removed by evaporation. For simplicity, we re-
strict our model to the diffuse radiation field used in AA07,
as the additional direct radiation component applies to the
later dissipation of the outer disc once the inner disc has
been evacuated, a phase of evolution of less interest to us.
We use the wind profile as outlined in the appendix A of
AA07.

An alternative mode of disc clearing is presented by
Armitage, Simon & Martin (2013) – ASM hereafter – mo-
ivated by studies which suggest that the conservation of
magnetic flux in a disc leads to an increase in the strength of
the magnetic disc wind as the gas surface density decreases.
This in turn drives an evolution of the viscosity parameter
$\alpha$, and an increase in the rate of viscous evolution with
time. This can result in a qualitatively different clearing,
by removing the outer disc first and then finally the inner
disc. We incorporate this as an alternative disc model by
neglecting the photoevaporation but including an evolution
of $\alpha$ as parameterised by ASM. This evolution is based on
the global conservation of magnetic flux in the disc, which
amounts to the conservation of the integral of $R^{1/2}\Sigma^{1/2}$
in our model.

Our default initial disc is

$$\Sigma_0 = \frac{1045g/cm^2}{R/1AU} \left( 1 - \sqrt{\frac{0.01AU}{R}} \right) \exp \left( -\frac{R}{20AU} \right)$$

(2)

which is of similar form to that of AA07 but more compact,
as befits our interest in the inner regions of the disc. Our
model for the initial deposition of solid particles is drawn
from Hughes & Armitage (2012), setting the condensible
mass fraction to be 0.00491 interior to the water ice line
(whose value is taken to be at 3 AU), 0.0106 between the
water ice line and the methane ice line (taken to be at 15 AU),
and 0.0149 exterior to that. We initially neglect grain growth
and so we assume all the condensible material is deposited at
the beginning and we thereafter simply follow the dynamical
evolution. We will discuss growth effects in §5.

4 SOLID PARTICLE EVOLUTION

The solid particles that condense out of the gas phase must
eventually grow into larger bodies to form planets. How-
ever, there are several significant hurdles along the path to
planet formation. The first is that, as small particles grow
larger, their coupling to the gas weakens and the resulting
difference in orbital velocity means that they are subject
to aerodynamic drag forces. This causes them to spiral
inwards towards the star (Whipple 1972; Weidenschilling
1977a), where they may be lost. We incorporate this into
our model using the formalism of AA07, based largely on
Takeuchi & Lin (2002), in which the radial velocity of each
particle is given by

$$u_d = \frac{\tau^{-1}u_k - \eta \dot{\Sigma}}{\tau + \tau^{-1}}.$$  (3)

The quantity $u_d$ represents the radial velocity of the gas
due to the viscous evolution, and $u_k$ is the Keplerian orbital
velocity at distance $R$. Thus, as the parameter $\eta$ (defined
below) becomes non-negligible, the solids will begin to evolve
radially with respect to the gas. The non-dimensional stop-
ing time $\tau$ is given by

$$\tau = \frac{\pi \rho_d s^2}{2 \Sigma_g}$$

(4)

over most of the disc, where $\rho_d$ and $s$ are the density and
radius of a given grain. This quantity determines whether
the particles are well coupled to the gas ($\tau < 1$) or not. The
quantity $\eta$ reflects the differential motion between a particle
in a true Keplerian orbit and the gas, which is partially
supported by a radial pressure gradient,

$$\eta = -\frac{H}{R} \left( \frac{1}{\partial \log \Delta \Sigma / \partial \log R} - \frac{7}{4} \right).$$

(5)

The nature of the drag force changes depending on the size
of the particle relative to the mean free path in the gas. Over
the bulk of our disc, the drag force is of the Epstein form
(equation 4). However, in the outer part of the disc, at late
times, it can become of Stokes form

$$\tau = \frac{8m_p \rho_d s^2}{9\sigma_H \Omega \Sigma_g},$$

(6)

where $m_p$ is proton mass, $\sigma_H$ is the collision cross-section
of molecular Hydrogen[4] and $\Omega$ is the orbital frequency.

We must also account for diffusive effects due to gas
turbulence, which acts against particle density gradients
established by differential drag. Thus, we include a diffusive
velocity term

$$u_{diff} = -D \frac{\partial}{\partial R} \ln \left[ \frac{\Sigma_d}{\Sigma_g} \right]$$

(7)

where $\Sigma_d$ is the local dust density, and $D$ is the turbulent
diffusivity. The default assumption is to equate this with the
viscosity $\nu$ (defined as the Schmidt number $\nu / D = 1$).
Deviations from unity are possible, but our focus is on the
smaller particles, while proposed corrections are most im-
portant for larger particles in the marginally coupled limit,
as discussed by Youdin & Lithwick (2007). We assume the
diffusion coefficient is the same for all particle sizes, but that
the diffusion velocity of each particle size is determined by
the surface density of that species only.

1 Taken to be $2 \times 10^{-15}cm^2$ – see discussion in Chiang & Youdin
(2010)
4.1 Redistribution

Our model thus far represents a standard treatment of the evolution of both gas and solids in an evolving protoplanetary disc. To this, we now add the hypothesis that solid material is entrained by a wind or jet in the inner disc (Liffman & Brown 1995; Shu et al. 1996; 2001; Salmeron & Ireland 2012; Bai & Stone 2013) and transferred back to the outer disc. The original Shu et al. model focussed primarily on redistribution only as far as the asteroid belt, but Hu (2010), motivated by the StarDust results, reviewed the aerodynamic requirements for redistribution in an X-wind model and found that, with uncertainties due to outflow and disc geometries, particles of size in the range of microns to millimeters could be transferred as far as the Kuiper Belt regions of discs. Larger particles are less well coupled to the outflow and likely to return to the disc on smaller scales, while smaller particles are sufficiently well entrained that they are easily lost from the system entirely. Thus, it is possible to invoke such models to explain the observed composition of the Comet Wild-2 as well.

We incorporate these effects into our simple model by assuming that, when solid particles reach 0.05 AU, they are instantly transferred back to the outer disc, with an equal probability per unit area of landing between 35 and 90 AU. This keeps the entire solid inventory circulating between the inner and outer disc, although the gas disc is slowly being accreted onto the star or evaporated. We will examine the effects of varying the properties of the redistribution in §5.3

4.2 From Dust to Planetesimals

Our hypothesis of wind entrainment and circulation of solid material provides a potential solution to the first hurdle to planet formation, in that it prevents the accretion of the solid material by the star. There is a second well-known hurdle to planet formation, which is the difficulty of converting small, dust-size particles into larger bodies with the densities and tensile properties of planetesimals. Despite decades of work, there is little convincing evidence that this transformation can be achieved by incremental processes, and thus the best hope for forming planetesimals is the gravitational instability of a solid dust layer that sediments to the midplane (Goldreich & Ward 1973). However, this model has also proven difficult to implement because turbulent gas motions can prevent a sufficiently dense dust layer from forming (Weidenschilling 1980). In order for the solid surface densities to be high enough to overcome turbulent stirring, Youdin & Shu (2002) demonstrated that the local solid densities had to be enhanced by factors of at least several over traditional protoplanetary metallicities.

There have been a variety of proposals (see Chiang & Youdin 2010 for a review) for achieving such enhancements. One class of models rely on the backreaction on the gas from radial particle streaming (Youdin & Chiang 2004; Youdin & Goodman 2005; Johansen et al. 2007) to promote gravitational instability. However, this only works if the particles are big enough to decouple from the gas on timescales similar to the orbital time (τ ∼ 1), which requires growth to sizes well in excess of the micron-centimeter sizes considered here. Another set of proposals includes growth of secular modes (Ward 2000; Youdin 2011) to produce particle clumping. However, these models also require either large particles or low turbulent viscosities (α < 10−3) to produce realistic growth.

In our simple model, the global dust inventory remains in circulation, even while the disc slowly loses gas by accretion and wind loss. As a result, the traditional scenario for direct gravitational instability remains potentially viable, because the required overdensities will eventually come to pass, as the global solid/gas ratio is monotonically increasing, although the locations where the instability occurs will depend on the evolutionary details. These locations are what is of interest to us, as they will then dictate the initial conditions for the later stages of planetesimal accumulation.

Therefore, we adopt the Youdin & Shu (2002) – YS02 – model of planetesimal formation. Interpreting the YS02 critical dust surface density in terms of our disc model yields an expression for the critical dust surface density

\[ \Sigma_d = 0.033 g \cdot cm^{-2} \Sigma_g \left( \frac{R}{1AU} \right)^{1/4} s(\psi) \]  

where \( s(\psi) = (1 + \psi) \ln \left[ \left( 1 + \psi + \sqrt{1 + 2\psi} \right)/\psi \right] - \sqrt{1 + 2\psi} \)
and \( \psi = 4.3 \times 10^{-5} \Sigma_g / (R/1AU)^{7/4} \). As an example, for a gas surface density of \( \Sigma_g = 100 g \cdot cm^{-2} \) at \( R = 1AU \), this requires \( \Sigma_d / \Sigma_g = 0.18 \) for gravitational instability. This represents an enhancement factor of 37 over the original, in situ, ratio, although the precise value of the necessary enhancement may be uncertain (e.g. Gomez & Ostriker 2005; Shi & Chiang 2013).

Whenever the local surface density of dust exceeds the critical value, we assume the excess is transformed into planetesimals by gravitational instability and no longer evolves with drift or with the gas. This assumption is a good one until the planetesimals assemble into larger bodies, at which point they may migrate again by exchanging angular momentum with the disc gas. We shall assume that this latter process takes \( > 5Myr \) – the point at which our calculation ends. Therefore, the final result of our calculation is a deposition profile of planetesimals that result from the global evolution of the dust and gas populations, which may then serve as the initial conditions for the later assembly of larger bodies.

5 RESULTS

5.1 No Recycling

We begin with a reference model, in which the gas disc given by equation (2) is evolved, along with our model for dust drift, diffusion and formation of planetesimals included. However, in this reference model, there is no redistribution of material from the inner disc to the outer disc. Thus, the reference model represents the expectations for planetesimal formation if we adopt the standard picture of viscous gas evolution and dust drift. This model also requires a choice of the size of solid particles, as they will determine the overall drift rates. Figure 2 shows the evolution of a dust population of size 1mm, where particles are simply removed when they reach the inner edge. The dust population is substantially depleted within 0.3 Myr and completely removed within 1 Myr. Other sizes behave in a similar fashion, al-
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The top four dotted curves indicate the gas surface density profile at ages of 0, 0.1, 0.5 and 0.7 Myr respectively. The four solid curves indicate the surface density of a population of 1 mm dust grains at the same ages. We see that the dust is completely removed within 1 Myr in the absence of other effects. The bottom three dotted curves indicate the late time evolution of the gas disc, at ages 4.0, 4.04 and 5 Myr, and show the rapid depletion of the inner gas disc once photoevaporation becomes important.

beit with different timescales – larger dust is removed more rapidly and smaller dust is retained longer.

The gas disc shows the expected evolution, with the bulk of the mass moving inwards and accreting onto the star, with a small fraction moving outwards to conserve angular momentum. We see that the effect of the wind starts to have an influence after \( \sim 4 \) Myr, and that this rapidly causes a gap to form at \( R \sim 1\,\text{AU} \), and the gas interior to this is quickly accreted onto the star. The outer gas disc is slowly eaten away from the inside out by the wind mass loss.

The radial drift of the dust will enhance solid surface densities and potentially generate sufficient overdensities for planetesimal formation (Youdin & Chiang 2004), but studies in evolving gas discs have not found significant mass deposition (Hughes & Armitage 2010). In our model too, we find little planetesimal formation. Our models do satisfy the analytic criteria for particle pile-up identified by Youdin & Chiang, but the enhancements are not sufficient to generate gravitational instability without recycling (however, see §5.4).

**5.2 Simple Circulation**

The essential problem is that the radial migration of dust is too rapid in a protoplanetary disc for easy planetesimal formation. Figure 3 now demonstrates the effect of including our model for redistribution of the solid material back to the outer disc. This model uses the same parameters as the model shown in Figure 2 with dust of size 1 mm. After several radial travel times, the dust establishes a steady-state surface density profile in the disc, which is steeper than the original dust profile. As the gas disc evolves and the gas surface density decreases, the dust profile will eventually exceed the critical density at particular locations and thus planetesimals will form through gravitational instability. The deposition of planetesimals begins at \( \sim 1\,\text{AU} \) but eventually extends inwards to \( \sim 0.2\,\text{AU} \). The steep dust density profile can be understood by the dynamics of dust in the \( \tau \ll 1 \) limit, which leads to a drift velocity which scales \( \propto R^{3/4} \) in the case where the gas surface density \( \propto 1/R \). Given this density profile, the dust population achieves steady state flux when \( \Sigma_d \sim 1/R_{d_{\text{ud}}} \sim R^{-7/4} \).

The speed with which material moves radially through the disc is the result of particle size, and so the normalisation of the steady state surface density profile varies with the size of the particle (the overall slope is the same as long as \( \tau \ll 1 \)). Figure 4 shows the final planetesimal deposition profiles of models in which all the particles have radii of \( s = 1\,\text{cm} \), \( s = 1\,\text{mm} \) and \( s = 10\,\text{\( \mu \)m} \) respectively. Also shown are estimates of the required rocky inventories for the planetary systems seen by radial velocity (RV) studies and Kepler, as well as for our own terrestrial and giant planets. For the inner disc we use the estimate of Chiang & Laughlin (2013), while we use a modification of the Weidenschilling (1977b) estimate of the minimum mass solar nebula (in that we restrict ourselves to the rocky component here). We see that circulating populations of small particles in the \( \tau \ll 1 \) regime are able to provide an inventory of planetesimals that matches the requirements imposed by both terrestrial and extrasolar observations. Note in particular that this model
Figure 4. The dashed line labelled MMKN is the surface density profile advocated by Chiang & Laughlin (2013) as a Minimum Mass Kepler Nebula. The dashed histogram labelled MMSN is the minimum-mass solar nebula of Weidenschilling (1977b), although we have restricted ourselves to an inventory of the solid material in the Solar System (assume 5 $M_\oplus$ cores for the outer Solar System planets). The dot-dashed line is the solid surface density estimate by Pollack et al. (1996) for the formation of giant planet cores. The green curve represents the planetesimal deposition in our model for a dust component composed of 1 cm (large) particles, the blue curve is for a model in which particles have size 1 mm, and the red curve shows the equivalent result when the particles are composed of 10 $\mu$m (small) particles, which move through the disc more slowly.

This provides a rationale for the smooth, quasi-power-law distributions usually adopted in planet formation models.

5.3 Size Distribution

A proper model for the evolution of the small bodies would also include a model for particle growth over time, which would couple the chemistry and the dynamics of small bodies in the disc. Such a calculation is well beyond our simple model, but we can anticipate some of the consequences of grain growth by considering a composite model of sizes designed to examine the differential motion of both small and large particle components in §5.2.

Our single size distribution shown in Figure 8 was chosen on the basis that the evidence from solar system meteorites suggests that the size distribution of chondrules peaks between 0.1–1 mm (Scott & Krot 2005) and thus a dust population of such particles offers a reasonable simple model of the underlying constituents. However, if this is the result of aerodynamic sorting in the formation of the chondrites (e.g. Cuzzi, Hogan & Shariff 2008), then the original size distribution of the nebular solids may be different.

Thus, we consider a model in which the solids are distributed in proportions of 10% large (1 cm) particles, 20% medium (0.5 mm) particles and 70% small (10 $\mu$m) particles. These proportions are applied at all radii in the initial construction of the dust profiles. This is intended to model a more primitive dust distribution, to see how the resulting planetesimal population is affected. The resulting distribution is shown in Figure 5.

In Figure 5 we see that the first planetesimals to form are those at $\sim 0.2–0.3$ AU, after only 0.3 Myr. The composition of these planetesimals is dominated by the large particles, whose profile is most concentrated in the inner disc and whose radial mobility is responsible for achieving the overdensity necessary for gravitational collapse. However, by 1 Myr we see that the planetesimal formation is starting to extend outwards to the terrestrial planet domain, and eventually the final distribution extends out to $\sim 10$ AU. Figure 6 shows the distribution of sizes that are removed from the dust disc by planetesimal formation over the full 5 Myr history of the disc. We see that larger particles dominate the inventory at small scales, with progressively smaller particles being incorporated further out and at later times.

In summary then, the choice of size distribution does not significantly change the amount of mass distributed in planetesimals inside 1 AU, but can influence the location of the first planetesimals to form (larger particles move the location inwards) and how much mass is formed in planetesimals are scales of several AU (smaller particles enhance the mass on larger scales).

Figure 7 shows the enclosed mass in planetesimals as a function of $R$ in the model of Figure 5. We see that $\sim 35 M_\oplus$ is deposited within 1 Myr inside 1 AU. After 2 Myr, this is supplemented by an additional $45 M_\oplus$ that is deposited out as far as 10 AU. For comparison, we also show the final mass...
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Figure 6. The solid curve indicates the surface density distribution of material that was removed from our dust evolution due to gravitational instability. The long dashed curve refers to the 1 cm particles, the short dashed curve to the 0.5 mm particles, and the dotted curve to the 10 $\mu$m particles. We see that solids that form on scales $> 1$AU are dominated by the smaller particles, while the material at $\sim 0.1$AU is dominated by the larger particles.

deposition profile from the single size model in Figure 5. In this case the bulk of the mass is deposited inside 2 AU.

The mass inventory in planetesimals laid down in this fashion may provide the starting conditions necessary for a variety of planetary formation scenarios. The assembly simulations discussed in Hansen & Murray (2012, 2013) require anywhere from 25–50 $M_\oplus$ of rocky material interior to 1 AU, depending on the mass inventory of the observed system. Assembly of giant planet cores in the solar system requires 10–20 $M_\oplus$ of material on scales $\sim 3$–10 AU, which is also realised if there is sufficient mass in particles smaller than 1mm.

5.4 Wind Clearing

We have also investigated an alternative model due to Armitage, Simon & Martin (ASM), in which the disc is cleared not by photoevaporation, but rather by the amplification of the magnetic field in the disc and a resulting acceleration of the viscous evolution at late times.

Our calculations suggest that the specific mechanism of disc clearing does not qualitatively affect the mass deposition interior to 1 AU, but may influence the amount of planetesimals formed on larger scales. Figure 8 shows the equivalent of Figure 5 but using the ASM model rather than the AA07 model, with an initial parameterisation equivalent to the $\beta_z = 10^5$ model of ASM (chosen to clear the disc on a similar timescale to the photoevaporative model). We include the same distribution of particle sizes, and find that the deposition of planetesimals once again starts on scales of $\sim 0.2$AU after 0.3 Myr and spreads slowly outwards on timescales of Myr. The only real difference between the final planetesimal mass profiles is a slightly more extended disc at the outer edge, driven by the fact that the late-time decrease in the gas surface density is more rapid in this model.

The role of disc winds could have a larger effect on small scales if they are capable of removing angular momentum without driving MHD turbulence. Bai & Stone (2013) find that turbulence can be suppressed if there is sufficient vertical field threading the disk, with the disk wind able to carry away the angular momentum necessary to facilitate accretion. Therefore, we have run the same model as in Figure 3 but with the diffusive contribution to the particle velocity set to zero interior to 10 AU. The resulting evolution is shown in Figure 9. Two differences in the planetesimal deposition are notable. The first is that the deposition occurs much more rapidly (starting at 0.1 Myr and substantially finished by 1 Myr). The second is that the profile extends inwards farther, indeed as far as the wind launching radius.

Both features are the result of the fact that the turbulent diffusion acts to smooth out a particle pileup – acting against the inspiral exterior to a local maximum in the dust density, but accelerating the inspiral interior to it. Without this contribution, our dust evolution looks a lot more like the model presented in Youdin & Chiang (2004), wherein the required overdensity for gravitational instability results purely from the concentration of the solids towards the interior of the disk. However, the depletion of the dust is again quite rapid and possibly at odds with observations of young star forming regions.
5.5 Imperfect Retention

Our simple model assumes that the gas is slowly lost from the system, but that solids circulate indefinitely. The result is that gravitational instability and planetesimal formation is inevitable. How robust is this consequence in the face of the inevitably imperfect retention of solids in a more realistic model? Some solid material may remain entrained with the gas that is accreted onto the star, and some material may be carried to infinity by the outflow. Figure 10 shows the evolution of the same model as Figure 3 (dust contained in 1 mm particles), but with a model which incorporates mass loss. In this case mass is lost from the inner edge of the disc at the same rate as it is added back at the outer edge i.e. a 50% retention fraction with each cycle. Not surprisingly, the dust is depleted more rapidly, and with much less planetesimal formation. However, the dashed line does show that some planetesimals do form, with a concentration between 0.5–1 AU. The final amount of mass in solids is \( \sim 7M_\oplus \), which actually makes an excellent initial condition for assembly of systems like that of the terrestrial planets of our own solar system (Hansen 2009), although it lacks the solid inventory on smaller scales that other systems require. Since the loss rate is determined by the rate at which material passes through the inner edge of the disc, this means that larger particles are lost more rapidly and smaller particles are retained longer.

Figure 11 shows the impact of dust loss on our simple model of a composite population. The solid curve indicates the planetesimal deposition result from the closed box model of Figure 5 at ages of 1 Myr and 2 Myr. The dotted line is
What goes around, comes around

6 DISCUSSION

The results of these calculations suggest that a protoplanetary disc with a circulating dust component will naturally produce conditions that allow for the formation of planetesimals via gravitational instability, and with a substantial mass deposition interior to 1 AU. This offers a promising route to the formation of planetary systems by in situ assembly on these scales (Hansen & Murray 2012; 2013; Chiang & Laughlin 2013). Of course, there are still several uncertainties that need to be addressed in matching the properties of the initial planetesimal population to that of the final planetary system.

6.1 Which Class of Planets are formed?

The formation of planetesimals is a necessary step on the road to forming a planet, but the conditions under which the subsequent assembly takes place will determine what kind of planet ultimately results. The first planetesimals to form in this model do so quite early, within 0.5 Myr of the original condensation from the nebula. This occurs when there is still substantial gas present in the disc and thus the future assembly into protoplanets will likely be affected by interactions with the gas, which can affect both the mass inventory and potentially the radial location. Figure [12] shows the relative mass in both gas and planetesimals in both the composite size model and the one in which all dust is ~ 1 mm, for both solids is small, if dust particles make many passages through the disk and are lifted each time by the outflow, then the energy required to lift the dust to large radii many times may start to affect the energetics of the outflow.

For a single size particle distribution, with a characteristic disc traversal time $\tau$, the particles will make $N \sim T/\tau$ passages through the disk during a global lifetime $T$ (which may be taken as the time to start forming planetesimals, which remove the dust from circulation). This means that gas drag from the wind must supply sufficient binding energy to lift a mass $\sim NM^2_\tau$ to the outer part of the disk. As long as this is substantially less than the gas mass removed in the outflow, it will not have a significant effect on the outflow dynamics. For our default model with mm-size particles, $\tau \sim 2 \times 10^4$ years and $T \sim 2 \times 10^5$ years, so that dust makes $\sim 10$ passages through the disk before being absorbed into planetesimals. For global metallicities $\sim 0.01$, this means that the outflow dynamics are not strongly affected as long as the outflow carries more than 10% of the gas mass that flows inwards from the disk to the star.

For dust populations with a size range, larger particles make more passages through the disk in a finite time, and smaller particles fewer. Thus, for distributions considered here (e.g. in Figure [4]), with more of the mass in smaller particles, the energy requirements for recirculation are well within the energy supplied by the outflow. On timescales $> 0.1$ Myr, the mass flux in the outflow must necessarily drop as the gas disk mass drops, but the circulating dust mass also drops as the mass turns into planetesimals on this timescale, so that the ability of the outflow to lift solid material does not appreciably limit the end result of the circulation.

5.6 Energy Limits on Circulation

The recirculation of solids requires that gas drag from the outflow accelerate particles until the outflow gas density drops low enough for the particle to decouple from the drag force and fall back to the disk. Each time the gas lifts a particle out of the potential well it saps the energy from the outflow. Although the total mass fraction of the disk in

Figure 11. The two solid curves indicate the material removed from the dust population by gravitational instability in the closed box version of our model with a composite size population. The curves are shown for system ages of 1 Myr and 2 Myr. The dotted curve is the equivalent 2 Myr for a model in which 50% of the material that passes through the inner disc is lost on each passage. There is no dotted 1 Myr curve because no solids form that fast in this model. The dashed curves show the case when only the small particles (which still comprise 70% by number) are subject to the 50% loss on each passage. Larger particles are retained, so that the results look more similar to the closed box case.

the equivalent for a model in which particles of all sizes are subject to the same 50% loss on each passage used in the model in Figure [10]. We see that the biggest change is the reduction in the amount of mass deposited into planetesimals at small radii. This is because these are composed preferentially of the larger particles, which have shorter circulation times and therefore make more passages through the inner disc per unit time. As such, they are preferentially depleted in this simple model. Perhaps a more realistic model is to deplete only the smallest particles, as Hu (2010) demonstrates that these are the most likely to be strongly coupled to the outflow and lost from the system. The dashed line in Figure [11] indicates the consequence for this model, in which the overall deposition is only slightly reduced from the closed box model. This suggests that the broad features of the planetesimal deposition are robust to a moderate amount of loss in the circulation and that the component of particles with sizes $\sim$ cm or larger are the most likely to be depleted in the final accumulation.
the inner disc (defined here as $R < 1\text{AU}$) and the outer disc ($1\text{AU} < R < 100\text{AU}$). In the case of the inner disc, the amount of mass in solids becomes comparable to the gas within 0.5 Myr.

In models in which the disc clears via photoevaporation, such as those of AA07, the gas interior to 1 AU is not evaporated from the system, but accreted onto the star. Thus, the eventual disposition of the remnant gaseous disc will require it to either be accreted or cross the orbits of the final planets to get to the central object. As a consequence, this remnant gas disc may have dynamical consequences for the final planetary configuration, but it does not have sufficient mass to overwhelm the rocky inventory available for forming planets. Indeed, much of this surviving gas may ultimately be accreted by the planets rather than the star, since observations suggest that many of the newly discovered planets are predominantly rocky but possess sufficiently massive gaseous envelopes that they must have accreted some gas from the nebula (e.g. Lissauer et al. 2013). In the case of the model shown in Figure 3, the gas/planetesimal mass ratio is $\sim 3 \times 10^{-4}$ interior to 1 AU at the point when photoevaporation decouples the outer gas disk from the inner gas disk. Lopez & Fortney (2013) suggest a characteristic value of the Hydrogen to rock ratio is more like $\sim 1\%$, which would require capture of the envelope on slightly shorter timescales $\sim 3$ Myr (Figure 12).

Exterior to 1 AU, there is a delay of 1–2 Myr before a population of planetesimals begin to accumulate. Figure 12 demonstrates that the gas/rock ratio is more variable on these scales, depending on the exact size distribution of the underlying solids. Allowing for more massive discs can allow for the formation of rocky cores more rapidly, but all models show the same requirement that the assembly of giant planet cores needs to occur within a narrow window of 1–2 Myr, in order to capture sufficient gas from the nebula. This echoes the well-known constraint on the formation of giant planets (e.g. Pollack et al. 1996). The process can be helped if we allow for a higher metallicity in the gas. Figure 13 shows the same model as in Figure 3, but we have increased the original dust sedimentation by a factor of two to mimic an enhanced metallicity. We see that the planetesimal formation in this model meets the surface density requirements of Pollack et al. (1996) within 0.2 Myr, suggesting that there is sufficient mass to form giant planet cores and to accrete the gaseous envelopes. The fact that this process is enhanced in high metallicity models may help to explain the correlation between host star metallicity and giant planet frequency.

The last planetesimals to form are those on scales $\sim 10\text{AU}$, which result from the onset of gravitational instability during the last stages of the gas disc clearing. The gas-poor origins of this outermost rocky component provides a natural environment for the origin of Kuiper Belt analogues, and for the assembly of the gas-poor ice giants of the outer solar system (e.g. Goldreich, Lithwick & Sari 2004). These effects may be further enhanced in cases where the evaporation is enhanced by an external evaporation field (Throop & Bally 2005).
6.2 Aerodynamic Sorting

The composition of the material that assembles into planetesimals in a composite model also varies radially. Interior to ~0.5 AU, the planetesimals are dominated by larger particles (~cm sizes), while the planetesimals are dominated by medium sized particles between 0.5–1 AU, and smaller particles exterior to that. This natural aerodynamic sorting by particle size results from the different normalisations of the steady state surface density distributions, as determined by the radial drift velocity. Similar sorting is observed in the chondritic material of the solar system (e.g. Scott & Krot 2005), in which chondrite families show an internal size consistency although there is some variation between families, and has spurred models of sorting by turbulent processes (e.g. Cuzzi, Hogan & Shariff 2008). As we have shown, a dust population of this size can produce a planetesimal disc well suited to the in situ assembly of compact planetary systems. However, composite size distributions can also match this observation since mm-sized particles dominate the planetesimals in a composite model also varies radially. Interior to ~1 AU, with larger(smaller) particles favouring planetesimals on smaller(larger) scales.

Furthermore, isotopic analysis of solar system materials also suggests that the process of planetesimal assembly lasted for at least a few Myr, in that chondrules are inferred to be identifiably older (e.g. Connelly et al. 2008) than the oldest calcium-aluminum rich inclusions (CAI). This is also nicely matched by the timescales in our model, with planetesimals at scales ~AU taking >1 Myr to form, although the innermost materials assemble within 0.5 Myr.

6.3 Evolution of Dust Disks

Our baseline gas disc evolution is drawn from AA07, whose goal was to study the evolution of dust that is observed in young protostellar systems through the reprocessing of the stellar emission. This work was motivated by the observed persistence of infrared emission from dust grains throughout the TT phase (Andrews & Williams 2005), contrary to the expectation that the mm-sized dust grains should be removed by the radial drag forces discussed above (Takeuchi & Lin 2005). AA07 discuss replenishment by evolution and growth in the grain population. While such processes are quite likely, our model also alleviates much of the observational discrepancy, since dust is not lost from the system but continuously recycled back to large radii. The formation of planetesimals will also remove dust (until such time as it is replenished by planetesimal collisions), so that our model also predicts a systematic loss of observable dust over time, shown in Figure 14. We see that the dust decreases by two orders of magnitude on a timescale ~3 Myr, which is more palatable than the timescale for loss via radial drift, which can be one to two orders of magnitude smaller.

6.4 Abundance Anomalies in Host Stars

Another consequence of such a model is that the material accreted onto the star should be depleted in heavy elements. Our nominal model contains an initial mass of 0.03 M⊙ of gas, most of which is ultimately accreted onto the star. For an original global metallicity fraction ~0.015, this implies a total mass of ~150 M⊕ in potential condensibles. However, using the condensation model of Hughes & Armitage (2012), we only condense 114 M⊙ into dust, with the difference being volatile material that remains in the gas phase in the inner disc. If we assume that only this remnant metal inventory is accreted with the gas, then we find that the material accreted onto the star should slightly depress the observed overall metallicity and enhance the volatile to refractories ratio slightly. To estimate the amount of the change, we assume that the surface convection zone during this protostellar stage is ~0.1 M⊙. If we add the above gas to this convection zone, we decrease the net metallicity by ~15%, or by 0.07 dex.

Some authors have claimed evidence for such metallicity trends (Ramirez et al 2009, Ramirez et al. 2011, Gonzalez Hernandez et al. 2013, Ramirez et al. 2013) in nearby stars, and have concluded that the Sun is depleted in refractories due to the formation of the terrestrial planets. However, it is not clear how easy it is to define a suitable control set of stars without planets, given that observations suggest at least 20%–50% of sun-like stars (Howard et al. 2010; Mayor et al. 2011) host low mass planetary systems, whose detectability is not assured. Nevertheless, our results suggest that such enrichments are observable, and do not require the assumption of late time accretion to avoid dilution of the signal, because the material removed from the accreted gas is more than an order of magnitude larger than that estimated using our, relatively low mass, terrestrial planet system (e.g. Chambers 2010).
We have presented a simple model for the evolution of a protoplanetary disc in which dust particles undergo radial drift inwards, but are then recycled to the outer parts of the nebula through the action of a stellar or disc wind. Although this model is quite simplistic, it provides a natural framework for the deposition of tens of earth masses of material into planetesimals on scales of 0.1–1 AU. This matches the required mass inventory to assemble the observed planets in situ.

There are also a variety of subsidiary issues that suggest further study is warranted. The retention of solids while gas is lost produces a natural evolution of the solid/gas ratio towards the limit where gravitational instability and planetesimal formation is likely to set in, obviating the need to invoke other physical mechanisms that require the existence of large particles or anomalously low viscosities. Much of the planetesimal reservoir is deposited within 1 Myr, which allows for the capture of residual gas from the nebula to explain the observed low mass Hydrogen envelopes, and matches the timescales inferred from the cosmochemical age dating of solar system meteoritic components. Furthermore, the gas mass on these scales is less than the mass in planetesimals, so that the resulting planets are likely to be as observed – with substantial Hydrogen envelopes that are nevertheless a minority constituent by overall mass. Furthermore, we find that increasing the metallicity of the disk has a larger effect on the mass of planetesimals formed on scales of several AU, and thus provides a rationale for why the giant planet frequency correlates with metallicity (Gonzalez 1997; Santos et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010) more strongly than the frequency of lower mass planets (Sousa et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010).

If the solid retention is not perfect, and loss rate is size dependant, it provides an aerodynamic sorting mechanism that may explain the characteristic sizes of chondrules in the solar system. Large particles (dimensions of cm or larger) make more passages through the disc and are thus likely to be more depleted via loss at the inner edge. Similarly, entrainment in the outflows is more likely to remove small particles (Hsu 2010), which suggests that particles in the size range 0.01-1 mm may have the greatest chances of retention and survival. The circulation of solid material also helps to explain the apparent chemical homogeneity of the solar system solid inventory (e.g. Villeneuve et al. 2009) and the ubiquity of material processed at high temperatures (e.g. Brownlee et al. 2012).

There several ways in which this calculation could be improved. The size evolution of the dust component has been ignored, although this is likely to provide an important feedback loop that may help to regulate the radial profile of the eventual formed planetesimals. We have also not extended the model forward to consider the formation of larger protoplanets and planets from our initial conditions. Nevertheless, we consider the above results encouraging in the sense that they manage to generate conditions that may plausibly be used to match to observed systems, at the reasonable price of invoking an assumption that has already proven useful in other contexts and may be required anyway to explain the well-mixed compositions of solar system bodies.

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