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DUST COAGULATION AND SETTLING IN LAYERED PROTOPLANETARY DISKS

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ABSTRACT

Previous models of dust growth in protoplanetary disks considered either uniformly laminar or turbulent disks. This Letter explores how dust growth occurs in a layered protoplanetary disk in which the magnetorotational instability (MRI) generates turbulence only on the surface layers of a disk. Two cases are considered: a completely laminar dead zone and a dead zone in which turbulence is "stirred up" from the MRI acting above. It is found that dust is depleted from high altitudes in layered disks faster than in uniformly laminar or turbulent disks. This is a result of the accelerated growth of particles in the turbulent regions and their storage in the laminar lower levels where they escape energetic collisions that would result in disruption. Thus, the regions of a protoplanetary disk above a dead zone would become rapidly depleted in small dust grains, whereas the outer regions will maintain a small dust population at all heights due to the disruptive collisions and vertical mixing from turbulence. This structure is similar to that inferred for disks around TW Hydra, GM Auriga, DM Tau, and CoKu Tau/4, which are depleted in dust close to the star but are optically thick at larger heliocentric distances.

Subject headings: planetary systems: protoplanetary disks — solar system: formation — stars: pre–main-sequence — turbulence

1. INTRODUCTION

The initial stages of planetary system formation involve the coagulation of dust in protoplanetary disks into planetesimals. Models of this process have been developed in order to interpret observations of protoplanetary disks (Dullemond & Dominik 2005; Tanaka et al. 2005; D'Alessio et al. 2006) or to understand the details of planetesimal formation in our own solar nebula (Weidenschilling 1980, 1984, 1997). An important factor in determining how growth takes place is whether or not turbulence is present in the disk, as it will increase the relative velocities between dust particles, leading to more frequent and energetic collisions. Previous efforts have focused on disks that were uniformly laminar or uniformly turbulent. However, the likely source of turbulence in protoplanetary disks, the magnetorotational instability (MRI), is expected to operate only in regions of the disk that are sufficiently ionized for the gas to couple to the local magnetic field (Balbus & Hawley 1991). Such regions are expected only at the extreme inner regions of the disk where the gas temperature exceeds ~1000 K allowing the gas to become collisionally ionized, and at the extreme surface layers of the disk where the absorption of X-rays and cosmic rays leads to ionization (Gammie 1996). The region that is not ionized sufficiently, which would likely be the disk midplane in the planet formation region, is termed the "dead zone."

The thickness of the surface layers that are significantly ionized depends, in part, on the dust concentration that is present. Sano et al. (2000) demonstrated that grain surfaces allow for the rapid recombination of ions and electrons, thus keeping the ionization fraction low. Significant ionization occurs only after the available surface area of grains is reduced, either through the incorporation of grains into larger bodies or by the depletion of solids by settling toward the midplane.

In this Letter, particle growth and settling in a layered protoplanetary disk are modeled. Two cases are considered: that of a laminar dead zone ($\alpha = 0$) and that of a dead zone that becomes turbulent, although to a lesser extent ($\alpha_{\rm DZ} = 0.1\alpha_{\rm MRI}$), in agreement with the models of Fleming & Stone (2003). The focus here is to demonstrate the effect that the layered structure has on the vertical distribution of solids in protoplanetary disk. A more detailed model, which explores a wider parameter space, will be presented in a future paper. In § 2, the model and assumptions are described. In § 3, the results of different simulations are presented. The implications for protoplanetary disk observations and structure are discussed in § 4.

2. MODEL DESCRIPTION

The evolution of the number density, n, of particles of a given mass, m, and radius, a, at a given height, z, above the midplane of a protoplanetary disk is given by

$$\frac{\partial n_m}{\partial t} = \frac{\partial}{\partial z}\left[\mathcal{D}_z \rho_g \frac{\partial}{\partial z}\left(\frac{n_m}{\rho_g}\right)\right] - \frac{\partial}{\partial z}(n_m v_z) + \frac{1}{2}\int_0^m K_{m', m-m'} n_{m'} n_{m-m'}\, dm' - n_m \int_0^\infty K_{m, m'} n_{m'}\, dm' + S_m. \quad (1)$$

The first term on the right-hand side of the equation describes the vertical diffusion that takes place due to turbulence, where D_z is the diffusivity [taken to be the local turbulent viscosity of the particles, $\alpha c H/(1 + St)$, where St is the local Stokes number of the particle] and ρ_g is the local gas mass density. The second term on the right-hand side describes the vertical settling due to gravity, where v_z is the settling rate determined by the balance of gravity and the drag force due to movement through the gas. The drag force on the particles is found using the laws given in Tanaka et al. (2005). Finally, the integral terms on the right-hand side of the particle represent the changes that occur due to coagulation, where the first term describes the creation of particles of mass m through collisions of smaller ones and the second term represents the loss of particles due to incorporation into larger solids. The K factors are the kernels, representing the product of the collisional cross section of the particles, $\pi(a_1 + a_2)^2$, with the relative velocities

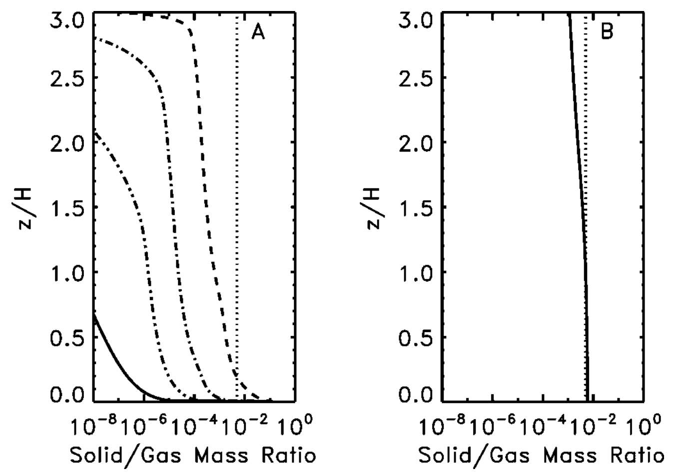

FIG. 1.—Plotted are the vertical distribution of solids at 1 AU for a uniformly laminar disk (A) and a uniformly turbulent disk (B) at $t = 1$ (*dotted line*), 1000 (*dashed line*), 10^4 (*dash-dotted line*), 10^5 (*dash–dot-dotted line*), and 10^6 yr (*solid line*). In the case of the turbulent disk, a steady state is achieved after ∼1000 years, in which particles are created as readily as they are destroyed.

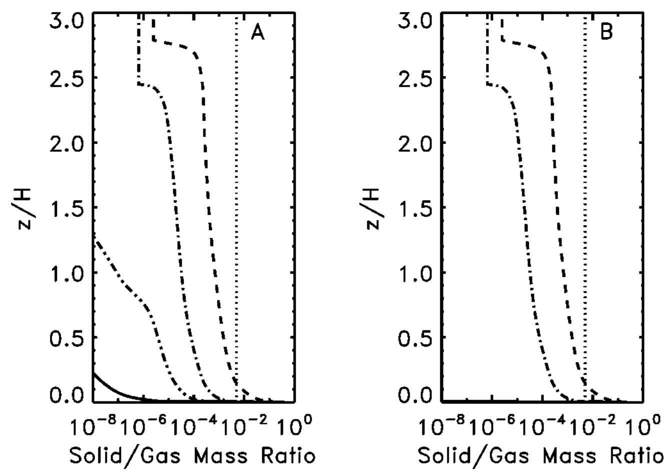

FIG. 2.—Vertical distributions of solids at 1 AU in a layered protoplanetary disk for a laminar dead zone (A) and a dead zone that gets stirred up from the active region above (B). The lines represent the same times described in Fig. 1. The 10^5 and 10^6 yr marks for case B are absent as all the mass of solids has been incorporated into large bodies at the midplane at these times.

between those particles. The relative velocities arise due to Brownian motion, differential settling, gas drag (radial and azimuthal components), and turbulence (when present). In the case of turbulence, the relative velocities are found as described in Dullemond & Dominik (2005).

Collisions may also result in disruption when velocities are large. A simple model is used in which collisions are assumed to be destructive if the total kinetic energy is greater than the strength of the sum of the two masses, $(m_1 + m_2)q^*$. In the case of a destructive collision, all of the mass of the two colliding bodies is assumed to be dispersed into the smallest sized particles considered here (this is represented by the source term in eq. [1], S_m). Here, a strength of $q^* = 1.25 \times 10^5$ ergs g^{-1} was assumed for all bodies, independent of size. This strength corresponds to bodies of equal sizes being disrupted at collisional velocities in excess of 10 m s^{-1}. This is likely a conservative estimate as Wurm et al. (2005) found that aggregation can occur at velocities as high as 25 m s^{-1}.

The disk considered here is assumed to have surface density and temperature structures given by $\Sigma(r) = 2000(1/r\ \mathrm{AU})$ g cm^{-2} and $T(r) = 300(1/r\ \mathrm{AU})^{0.5}$ K, respectively. The disk is assumed to be isothermal with height above the disk midplane. Inside of the snow line (taken to be 4 AU, where $T = 150$ K), dust is initially suspended at a solid-to-gas mass ratio of 0.005 with a particle density of 1.5 g cm^{-3}. All solids are initially distributed as particles 0.1 μm in diameter. In all cases, the disk is assumed to extend to 3 pressure scale heights, H, above the disk midplane.

A simplified model for the growth of the MRI-active region is used here. The MRI is initially assumed to be active in the upper 1 g cm^{-2} of a given location of the disk. As the available surface area of the grains decreases, either through coagulation or settling, the active layer grows. The MRI becomes active below the top 1 g cm^{-2} of a disk when the total mass denity of dust smaller than $a = 1$ μm is less than 10^{-4} times the original mass density of solids (Sano et al. 2000). The active layer is not allowed to expand beyond 100 g cm^{-2}, marking the maximum penetration depth of ionizing radiation, in agreement with Gammie (1996). The MRI region is assumed to have a turbulence characterized by $\alpha = 10^{-2}$. In those cases specified, the dead zone develops a value of $\alpha = 10^{-3}$ when $\Sigma_{\mathrm{MRI}}/\Sigma_{\mathrm{DZ}} = 0.1$ to mimic the results of Fleming & Stone (2003).

3. RESULTS

Figure 1 shows the evolution of the vertical distribution of solids at 1 AU for the cases of a uniformly laminar disk and a uniformly turbulent disk, which are the typical cases that have been considered when modeling dust coagulation in protoplanetary disks. In the case of the laminar disk, dust growth originally occurs due to the Brownian motion that the small grains experience in the gas. As larger grains form, they begin to settle toward the midplane, with higher settling velocities at higher altitudes. These larger bodies “rain out” from these high altitudes, sweeping up the small grains that are present on the way to the midplane. As a result, the upper layers of the disk are first depleted in dust, with the lower altitudes becoming more depleted with time. Essentially all of the mass of the solids becomes incorporated into planetesimal-sized bodies that reside at the midplane.

In the uniformly turbulent case, little depletion actually occurs, as turbulence inhibits the growth of bodies beyond a certain point. The additional relative velocity between particles as a result of turbulence produces a situation that has been referred to as the “meter-sized barrier” (Weidenschilling 1984; Cuzzi & Weidenschilling 2006). Turbulence allows particles near 1 m in size to develop relative velocities with respect to one another that results in disruptive collisions. The disruptive timescale for these bodies is less than their growth timescale through collisions with smaller particles. As a result, growth beyond this size is frustrated, and small dust is constantly resupplied to the nebula through these collisions and mixed vertically by turbulent diffusion. Thus, the vertical distribution of material reaches a steady state situation after ∼1000 years, where dust is somewhat depleted at high altitudes, but only by a factor of a few.

Figure 2 presents the results for layered protoplanetary disks, where the turbulent region begins in the extreme upper layers of the disk and grows with time as dust is depleted, with both a perfectly laminar dead zone and a dead zone that becomes turbulent when the Fleming & Stone (2003) criteria is satisfied. Initially, the dust distributions in these two cases evolve identically. In the MRI-active layers, particle growth is rapid compared to the dead zone, as turbulence increases the relative velocities between particles, leading to more frequent collisions. While growth is somewhat frustrated as larger bodies form and collisions become more energetic and disruptive, some fraction of larger bodies continuously settle to the dead zone and thus are removed from the MRI-active layer. As there is no turbulence in the dead zone during these early times, and thus no vertical diffusion, there is no way to resupply the MRI-active region with solids.

Particles in the dead zone continue to grow as described for the uniformly laminar disk, with much of the mass concentrating at the midplane and being incorporated into larger bodies. After 50,000 years, the Fleming & Stone (2003) criteria, where $\Sigma_{MRI}/\Sigma_{DZ} = 0.1$, is met, and turbulence is stirred up in the dead zone. At this time, much of the mass of the solids is found at the midplane in bodies 5–200 m in radius, as seen in Figure 3. This size range is beyond the "meter-sized" barrier. Thus, when the dead zone becomes turbulent, the small dust particles that remain can grow through mutual collisions, but only to the barrier size, at which point their collisions become disruptive and maintain a population of fine dust that gets mixed vertically. However, the turbulence also increases the rate at which dust particles collide with the larger bodies at the midplane, which results in faster accretion of the dust by the larger bodies that have already formed. As a result, the growth of the large bodies is then accelerated by the presence of turbulence since collisions are not destructive, meaning that these large bodies are able to rapidly deplete the population of small particles that remain in the disk.

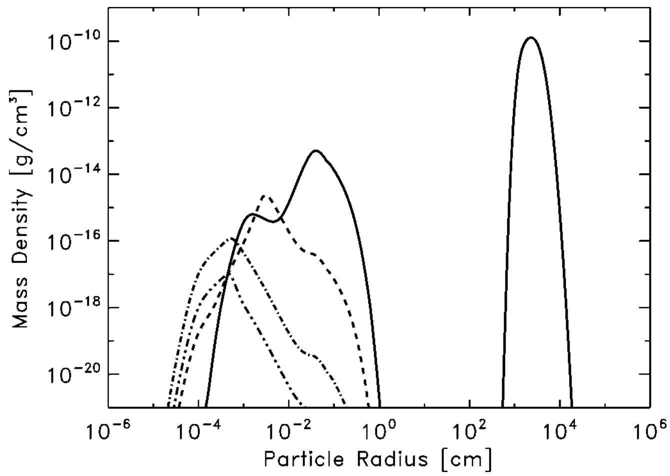

FIG. 3.—Plotted are the mass density of particles in a layered disk when the MRI-active region grows massive enough to "stir up" turbulence in the dead zone. The lines represent the distribution of particles at the midplane (*solid line*) at one scale height (1*H*; *dashed line*), 2*H* (*dash-dotted line*), and 3*H* (*dash–dot-dotted line*).

4. DISCUSSION

The results presented here show that in layered protoplanetary disks, the active regions above the dead zone become depleted of dust on short timescales, particularly when compared to the cases of a uniformly laminar or turbulent disk. While radial transport in the MRI-active layers has been neglected, the timescale for dust to be delivered to the dead zone from above is short. Thus, it is unlikely that radial transport would be sufficient to replenish dust in the active layers to levels far above those seen here. Even turbulence generated by a particle-rich layer at the midplane would be ineffective as the vertical scale of such turbulence is expected to be much less than that considered here (Weidenschilling 1997). This depletion of solids at high altitudes will have important consequences for modeling and interpreting observations of protoplanetary disks.

Dust at high altitudes (3–5 scale heights) absorbs and scatters radiation from the central star and determines how radiation is processed by the disk (Chiang et al. 2001; D'Alessio et al. 2006). If dust is absent from this region, or even depleted, it will drastically affect this processing. In particular, D'Alessio et al. (2006) found that while dust depletions in the upper few scale heights would not alter the surface temperatures of the disk, midplane temperatures would decrease because less radiation would be processed and directed to the disk interior. This would be particularly important in dead zones that do not generate heat from viscous dissipation.

The radial extent of the dead zone would vary from disk to disk and depends on such factors as the strength of the magnetic field, the surface density distribution of the disk, the size of the dust particles, and their composition (Sano et al. 2000). However, the general expectation is that beyond the point where the dead zone terminates, the disk will be MRI-active at all heights and therefore uniformly turbulent. Thus, this would create a situation where dust is depleted in the inner disk but is present, and at high altitudes, in the outer parts of the disk. Such structures have been inferred for disks around TW Hydra, GM Auriga, DM Tau, and CoKu Tau/4 (Calvet et al. 2005; D'Alessio et al. 2005). These disks appear to be significantly depleted in dust in the inner disk, but they are optically thick at larger radii. The transition between these two regions is thought to be very sharp, with the inner edge, or wall, of the optically thick region being directly illuminated by the central star. The clearing of the inner parts of the disk was originally attributed to a planet opening a gap, but it is thought that the high residual mass of the disk would lead to rapid inward migration due to disk torques (Calvet et al. 2005).

Based on the results presented here, it is possible that in some disks, the inferred wall represents the termination of the dead zone. Inside of the wall, most of the solids have settled to the midplane and have been incorporated into planetesimals, whereas outside of the wall, the growth of large bodies has been inhibited by the presence of turbulence, as in case B of Figure 1. Not only would this explain why the outer regions are optically thick, but it would also explain why dust is present at such high altitudes outside of the wall but nearly absent inside of it. The minor amount of dust inside of the wall in the disks around TW Hydra and GM Auriga may be tied to the fact that these disks are still accreting onto the central star. This implies that nonnegligible mass transport is taking place through the disk (Calvet et al. 2005), and thus small grains may be carried inward from the optically thick outer disk by the net advective flows associated with disk evolution. CoKu Tau/4, on the other hand, is not accreting significant amounts of mass and therefore would be unable to resupply the inner region with fine dust at a significant rate. For those disks in which no obvious inner gap appears, it is possible that either the dead zone spans a negligible region of the disk or the dead zone is being stirred up by other effects. For example, gravitationally unstable disks have been shown to be capable of generating turbulence locally or to produce large-scale transport of fine dust on short timescales (Boss 2004; Boley & Durisen 2006).

These results also offer a potential way of interpreting the meteoritic record of how solids grew in our own solar nebula. Recent results suggest that many iron meteorites are just as old as the oldest known objects in our solar system, the calciumaluminum–rich inclusions (CAIs; Kleine et al. 2005). Previously, it was thought that chondritic meteorite parent bodies represented the oldest accreted planetesimals in our solar system. With chondrules, the dominant components of chondritic meteorites, being typically 1–3 million years younger than CAIs, nebular turbulence had been invoked as a way of delaying the formation of large bodies until this time period. It has also been argued that other properties of chondritic meteorites, such as the narrow size range of chondrules in a given meteorite, are easier to understand if they formed in a turbulent nebula (Cuzzi et al. 2001, 2005).

The layered disk model presented here offers a possible way to allow for the early formation of large bodies and the subsequent formation of chondritic meteorite parent bodies in a turbulent environment. Large bodies could form during the initial stages of disk evolution when the MRI operated only in the extreme upper layers of the disk. The midplane region of the disk would be laminar and would allow for the rapid formation of kilometer-sized bodies on relatively short timescales. These bodies could grow further through mutual collisions and would likely contain enough ^{26}Al and ^{60}Fe that they would differentiate and develop iron cores. As the MRI-active region in the upper layers of the disk grew due to dust depletion and surpassed the critical size as given by Fleming & Stone (2003), the entire interior of the disk would become turbulent. While the case considered here suggested that the dust that remained in the disk when the dead zone became turbulent would be rapidly accreted by the larger bodies, this treatment neglected the effects of chondrule formation events or the possible formation of chondrite parent bodies directly from dust by turbulent concentration (e.g., Cuzzi et al. 2001). Additionally, if turbulence is present in the disk midplane, mass and angular momentum transport could occur through the dead zone, allowing dust to be resupplied to the inner disk from larger heliocentric distances. This would provide a turbulent environment filled with matrix and chondrule precursors in which chondritic meteorite parent bodies could form.

In conclusion, the upper layers of turbulently layered protoplanetary disks are depleted in dust more rapidly than either uniformly laminar or uniformly turbulent disks. This is because the turbulence in the upper layers of a disk leads to the rapid production of large bodies that are then stored in the laminar midplane region of the disk. Even if the midplane region later becomes turbulent because it is stirred up from above, large bodies may grow from the “seeding” that occurs during the initial laminar phase. While the particular results of the model are parameter-dependent, there are aspects of protoplanetary disk observations and the meteorite record of our own solar system that can be understood in the context of a layered disk. Future studies should investigate these effects in detail.

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