GRAIN RETENTION AND FORMATION OF PLANETESIMALS NEAR THE SNOW LINE IN MRI-DRIVEN TURBULENT PROTOPLANETARY DISKS

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ABSTRACT

The first challenge in the formation of both terrestrial planets and the cores of gas giants is the retention of grains in protoplanetary disks. In most regions of these disks, gas attains sub-Keplerian speeds as a consequence of a negative pressure gradient. Hydrodynamic drag leads to orbital decay and depletion of the solid material in the disk, with characteristic timescales as short as only a few hundred years for meter-sized objects at 1 AU. In this Letter, we suggest a particle retention mechanism that promotes the accumulation of grains and the formation of planetesimals near the water sublimation front or “snow line.” This model is based on the assumption that, in the regions most interesting for planet formation, the viscous evolution of the disk is due to turbulence driven by the magnetorotational instability (MRI) in the surface layers of the disk. The depth to which MRI effectively generates turbulence is a strong function of grain size and abundance. A sharp increase in the grain-to-gas density ratio across the snow line reduces the column depth of the active layer. As the disk evolves toward a quasi-steady state, this change in the active layer creates a local maximum in radial distribution of the gas surface density and pressure, causing the gas to rotate at super-Keplerian speed and halting the inward migration of grains. This scenario presents a robust process for grain retention that may aid in the formation of proto-gas giant cores preferentially near the snow line.

Subject headings: planetary systems: protoplanetary disks — solar system: formation — turbulence

1. INTRODUCTION

More than 200 extrasolar planets have been discovered with radial velocity surveys, corresponding to 10%–15% of the sample of mostly nearby solar-type stars (Marcy et al. 2005). In the current paradigm, the formation of both terrestrial and gas giant planets begins with the collisional growth of planetesimals, the latter only accreting gas once the solid cores have reached several Earth masses (Pollack et al. 1996). The growth rate of these protoplanetary embryos is determined by the surface density distribution of planetesimals, \( \Sigma_p \), in their nascent disks. In the typical construction of a planet formation sequence (e.g., Kokubo & Ida 2002; Ida & Lin 2004, hereafter IL04), authors have often utilized an empirical “minimum-mass nebula model” (MMNM) in which \( \Sigma_p = 10^{10} \rho_{\text{AU}} \) g cm\(^{-2} \), where \( \rho_{\text{AU}} \) is the radial distance from the central star. This Ansatz is based on the assumption that the planets in the solar system locally retained all the heavy elements and a fraction of the gas in the primordial solar nebula (Hayashi et al. 1985). Within the observationally inferred range of protostellar disk masses (Beckwith & Sargent 1996), gas giants can readily form near the water sublimation front or “snow line.” This model is based on the assumption that, in principle, grains at a few AU can be retained and then converted into planetesimals either through sedimentation followed by gravitational instability (Goldreich & Ward 1973; Youdin & Shu 2002; Garaud & Lin 2004) or through cohesive collisions (Supulver & Lin 2000) after the photoevaporation of disk gas increases Z above unity. However, the severe depletion of the disk gas will also limit the supply that the gas giants use to accrete their massive envelopes.

In this Letter, we propose a grain retention mechanism that can promote rapid planet formation around sublimation fronts in protoplanetary disks. We assume the disk evolution during the classical T Tauri phase to be regulated by a magnetorotational instability (MRI; Balbus & Hawley 1991). However, MRI only operates in regions with a sufficient ionization fraction to couple the gas to the magnetic field. The inner regions of typical protostellar disk are thermally ionized (Pneuman & Mitchell 1965; Umebayashi 1983). At greater distances from the disk center (\( r > 0.1 \) AU), stellar X-rays and diffuse cosmic rays ionize the surface layers of the disk down to a certain column density, \( \Sigma_i \) (Glassgold et al. 1997). Thus, the disk may have a layered structure in which the MRI-induced accretion flow occurs on its active surface; this surface surrounds a highly neutral and inactive “dead zone” (Gammie 1996). The magnitude of \( \Sigma_i \) depends strongly on the relative abundance and size distribution of grains (Wardle & Ng 1999; Sano et al. 2000). Across the snow line or the dust-destruction front, there are significant changes in the amount of solid material in the form of grains. In a disk with a solar composition, the total mass fraction in grains decreases by at least 50% due to the sublimation of water ice interior to the snow line (Lodders 2003). Efficient inward transport of solid materials combined with the slow diffusion of the heavy elemental vapor can further...
enhance the contrast in the grains’ surface density (Cuzzi & Zahnle 2004). This rapid radial change in dust properties and the corresponding rapid change in the column density in the active region lead to local maxima in \( \Sigma \), and \( \dot{P} \) in a steady state disk. As noted by other authors (Bryden et al. 2000; Haghighipour & Boss 2003), this pressure-gradient reversal induces a super-Keplerian \( V_r \) and causes solid material to build up near the local pressure maxima.

In order to highlight the dominant process, we adopt a simple, one-dimensional, steady state model for the gas distribution, in which the gas mass flux in the radial direction, \( M_g = 2\pi \Sigma V_r r \) (where \( V_r \) is the radial velocity of the gas), is independent of \( r \). Interior to 5 AU in a typical protoplanetary disk, the disk should rapidly relax to this quasi–steady state (Beckwith & Sargent 1996). In § 2, we present a simple analytical model for the structure of a disk with variable viscosity and describe the conditions under which these changes may induce a pressure-gradient reversal. In § 3, we present numerical results to show how these changes manifest themselves around the dust-destruction front and the snow line, at different stages in the disk evolution. Finally, we summarize our results and discuss their implications in § 4.

2. MODEL DESCRIPTION

We will parameterize our model in the framework of the familiar ad hoc \( \alpha \)-prescription in which the efficiency of angular momentum transport is approximated by an effective viscosity \( \nu = \alpha(r) c_s h \), where \( c_s \) and \( h = c_s /\Omega_k \) refer to the sound speed at the midplane and the isothermal density scale height, respectively (Shakura & Sunyaev 1973). However, we deviate from the standard model in that we allow \( \alpha \) to vary with \( r \). The Keplerian frequency around a star with mass \( M_* \) is \( \Omega_k = (GM_*/r^3)^{1/2} \). The surface density at each radius in a disk with mass accretion rate \( M_* = \Sigma_* M/(3\pi r^2) \) (Pringle 1981).

The interaction of the gas with the sedimented grains (super-centimeter size) leads to their orbital evolution. The speed of their migration depends on their sizes, and the radial velocity of the maximally affected particles is

\[
v_r = \frac{1}{2p} \frac{\partial \rho}{\partial r} \Omega_k^{-1}
\]

(see Weidenschilling 1977 for derivation). In most regions of the disk, \( P \) monotonically decreases with \( r \) so that \( V_r < \Omega_k r \), and gas drag causes the grains to undergo orbital decay. However, if \( \partial P/\partial r > 0 \), then \( v_r > 0 \), and particles will drift outward rather than inward. If we assume a vertically isothermal disk, the pressure at the midplane is given by \( P = \Sigma_0 c_s^2 / (2\pi h) \).

If we assume a power-law temperature distribution in the radial direction, \( T = T_0 r_0^\gamma \), and use the steady state \( \Sigma_* \), then \( v_r \), from equation (1) will be positive if

\[
r \frac{d\alpha}{dr} < - \left( \frac{3 - q}{2} \right).
\]

We can approximate a rapid radial variation in the viscosity at radius \( r_0 \) as a smoothed step function in \( \alpha \),

\[
\alpha(r) = \frac{(\alpha_1 - \alpha_2)}{2} \left[ 1 + \text{erf} \left( \frac{r_0 - r}{\Delta r} \right) \right] + \alpha_2,
\]

where \( \Delta r \) is the characteristic width of the transition zone. For this simple \( \alpha(r) \) prescription, the particle outflow condition is

\[
\frac{\Delta r}{r_0} < \sqrt{\frac{1}{\pi} \frac{\Delta \alpha}{\alpha} \left( \frac{3 - q}{2} \right)}.
\]

where \( \Delta \alpha = \alpha_1 - \alpha_2 \) and \( \alpha = (\alpha_1 + \alpha_2)/2 \).

In a layer-accreting disk, there is physical motivation to describe the variations in \( \alpha \) with respect to the depth of the region unstable to MRI turbulence. In this case, \( \alpha \) is the vertically integrated value, including both the efficient angular momentum transport from the active layers in the disk and a small residual contribution \( \alpha_0 \) from the MRI-stable region such that

\[
\alpha = \frac{\Sigma}{\Sigma_{\text{MRI}}} \alpha_{\text{MRI}} + \alpha_0.
\]

where \( \alpha_{\text{MRI}} = 1.8 \times 10^{-2} (\beta/1000)^{-1} \) is the appropriate scaling for MRI turbulence (Sano et al. 1998). For the plasma parameter \( \beta = P/(\rho m_p) \), we use \( \beta = 1000 \). For disks with weak magnetic fields, reasonable values for \( \beta \) are on the order of 100–1000 (Sano et al. 2000).

Although an actual detailed description of \( \alpha \) is not important for the effect that we consider here, it represents some mechanism of angular momentum transport in the “quiescent” part of the disk beyond the dust-destruction front (e.g., convective instability in the vertical direction [Lin & Papaloizou 1980], gravitational torques [Laughlin & Rozyczka 1996], linear Rossby wave instability [Li et al. 2000], baroclinic instability [Klahr & Bodenheimer 2003; Klahr 2004], linear stratrophic instability [Dubrulle et al. 2005; Shalybkov & Rüdiger 2005], etc.) so that it is possible for the disk gas to evolve into a quasi–steady state, in which \( M_* \) becomes an essentially independent function of \( r \). In the absence of any other angular momentum transport mechanism (i.e., \( \alpha_0 = 0 \)), a steady state is unattainable, and gas will continue to accumulate until another instability is generated. A pressure-gradient inversion can still develop, albeit it will be nontrivial to retain the accumulated grains if the disk becomes gravitationally unstable.

The steady state surface density profile is

\[
\Sigma_* = \frac{\dot{M}}{3\pi \alpha_0 c_s h} - \frac{\Sigma}{\Sigma_{\text{MRI}}} \alpha_{\text{MRI}} \alpha_0.
\]

The column depth of the region unstable to MRI turbulence can locally be described as a power law \( \Sigma \propto r^p \) when the total column depth \( \Sigma > \Sigma_* \). At a sublimation front in the layer-accreting region of the disk, the active region may be described locally as

\[
\Sigma_* = \left( \frac{r}{r_0} \right)^p \left( \frac{\Sigma_{A,1} - \Sigma_{A,2}}{2} \left[ 1 + \text{erf} \left( \frac{r_0 - r}{\Delta r} \right) \right] + \Sigma_{A,2} \right).
\]

\( \Sigma_{A,1} \) and \( \Sigma_{A,2} \) are the column depths at that radius, assuming the two different particle populations on either side of the transition. In this case, the particle outflow condition is

\[
\frac{\Delta r}{r_0} < \sqrt{\frac{1}{\pi} \frac{\Delta \Sigma}{\Sigma_{\text{MRI}}} \left[ \frac{\Sigma_{\text{MRI}}}{\Sigma_{A}} \left( \frac{3 - q}{2} \right) + p - 3 - \frac{q}{2} \right]}.
\]
due to the expected large decrease in viscosity, the condition stated in equation (4) can be most easily applied in the inner region of the disk near the dust-destruction front. The gas is thermally ionized until $T \approx 1000$ K, so the dust-destruction front is roughly coincident with the outer boundary of the thermally ionized region. At this location, the disk makes a transition from being completely MRI-active to having a very large gas column density that is stable to MRI. As the active region switches from covering the entire thickness of the disk to being virtually nonexistent in the presence of a significant population of small particles (Turner et al. 2007), we can utilize our simple $\alpha$ description from equation (3), where $\alpha_1 = \alpha_{\text{MRI}}$ and $\alpha_2 = \alpha_0$.

Due to the expected large decrease in viscosity, the condition stated in equation (4) is easily satisfied at the dust-destruction front for even rather broad transition regions. Therefore, we use this clean case to demonstrate the manner in which the pressure gradient is affected by the viscosity in a steady state disk. Figure 1 shows the effect for a particular $\alpha$ profile with $\alpha_0 = 10^{-3}$ for different power-law temperature profiles. While the surface density changes according to the temperature profile, the pressure gradient is very weakly dependent on temperature. We also show the evolution of an initially well-mixed population of maximally migrating particles. While a realistic population of particles will not accumulate as quickly as this maximally drifting population, this is illustrative of the efficiency of particle retention at the pressure maxima. It is also important to note that the location of the pressure maximum is exterior to the sublimation front, meaning that the material trapped in this region will not be lost due to sublimation.

3. RESULTS

3.1. Dust-Destruction Front

The modified step function in equation (3) can be most easily applied in the inner region of the disk near the dust-destruction front. The gas is thermally ionized until $T \approx 1000$ K, so the dust-destruction front is roughly coincident with the outer boundary of the thermally ionized region. At this location, the disk makes a transition from being completely MRI-active to having a very large gas column density that is stable to MRI. As the active region switches from covering the entire thickness of the disk to being virtually nonexistent in the presence of a significant population of small particles (Turner et al. 2007), we can utilize our simple $\alpha$ description from equation (3), where $\alpha_1 = \alpha_{\text{MRI}}$ and $\alpha_2 = \alpha_0$.

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3.2. Snow Line

A reversal of the pressure gradient around the snow line will only occur at certain stages in the disk evolution. In an MRI-driven disk, the structure of the disk at the snow line can be described in three stages. Initially, the column density at the snow line is very large, corresponding to a high steady state mass accretion rate. The MRI-active layer is negligible due to the presence of numerous small grains. If the mass accretion rate is high (as in disks around FU Ori systems), will increase to such large values that the disk will be unstable to gravitational instabilities (Laughlin & Bodenheimer 1994). The small contribution of the change in the active layer at the snow line will not be important in these early disks. Later, the mass accretion rate decreases, and/or the grains grow, so that the structure of the MRI-active layer strongly affects the total disk column depth. In this stage, there is a dip in the steady state surface density profile corresponding to the increase in viscosity interior to the snow line. In these disks, the pressure gradient is inverted, and solid material accumulates. Finally, the mass accretion rate, and therefore the surface density, will decline to the point that the entire disk is MRI-active, and this trapping mechanism will no longer be effective. Regardless of the grain properties, this stage will have occurred by the time the mass accretion rate drops to the level observed among the weak-line T Tauri stars.

To demonstrate these stages, Figure 2 shows the resulting steady state surface density profiles for a series of accretion rates and illustrative examples of $\alpha_0$ (not intended to constrain the possible range of $\alpha_0$). We approximate the size of the active layer from chemical equilibrium calculations to determine the linear stability to MRI turbulence (Ilgner & Nelson 2006 [model 4]; N. Turner 2007, private communication). In these
consistent calculation at this time. very weakly dependent on the temperature we neglect the self-
passively irradiated disk, but as the pressure gradient is only
the inactive shielded layers, forcing it to rotate at the local Kep-
Thereafter, the dust transfers angular momentum to the gas in
this radius becomes comparable to the amount of gas in the disk.
into the pressure maximum until the amount of solid material at
stable zones, the disk may be able to reach a quasi–steady state.

4. DISCUSSION AND CONCLUSIONS

We have demonstrated that, in a disk whose evolution is
dominated by the MRI-driven turbulence, the sensitivity of the
instability to the grain properties creates regions with radial-
pressure-gradient inversion and results in the accumulation of
migrating particles. This mechanism provides a potential res-
olution to the problem of grain retention in protoplanetary
disks. These radial-pressure-gradient inversions occur at the
sublimation fronts, such as the snow line, with a modest grain
depletion as long as the transition occurs over a short radial
extent.

In the presence of another viscous mechanism in the MRI-
stable zones, the disk may be able to reach a quasi–steady state.
Under these conditions, the solid material will continue to flow
into the pressure maximum until the amount of solid material at
this radius becomes comparable to the amount of gas in the disk.
Thereafter, the dust transfers angular momentum to the gas in
the inactive shielded layers, forcing it to rotate at the local Kep-
lerian speed and to diffuse to larger radii. The region of dust
accumulation then expands slowly outward. In the absence of
another source of viscosity, a steady state may not be attainable.
In this case, gas will continue to accumulate, maintaining a pres-
sure maximum that will trap solid material until other dust or
gas instabilities start to dominate the disk evolution.

The particles collected at the snow line should rapidly grow
through cohesives collisions. At the snow line, grains of all sizes
are likely to be covered with marginally molten frost that can
promote the cohesive nature of the collisions (Bridges et al. 1996).
The particles may also be able to grow past the “meter-
sized barrier” (Weidenschilling 1984; Cuzzi & Weidenschilling
2003). First, as at the pressure maximum, all material is moving
at Keplerian velocity; large objects will not be “sandblasted”
by smaller grains. If particles grow past the meter-size scale
to the regime where they are not well coupled to the turbulent
flow, there is no further barrier to their growth as there would
be at other positions in the disk. Additionally, as the particles
are collected in regions where the midplane is stable to MRI
turbulence, the question of whether meter-sized objects (cou-
pied to the largest eddies) will undergo destructive collisions
depends on the properties of whatever mechanism for angular
momentum transport may occur in the “dead zone.” If the disk
is weakly turbulent ($\alpha_s < 10^{-4}$) or if the transport of angular
momentum is due to a mechanism not involving turbulence,
then even this aspect of the “barrier” can be overcome.

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