PLANETESIMAL FORMATION IN MAGNETOROTATIONALLY DEAD ZONES: CRITICAL DEPENDENCE ON THE NET VERTICAL MAGNETIC FLUX

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ABSTRACT

Turbulence driven by magnetorotational instability (MRI) affects planetesimal formation by inducing diffusion and collisional fragmentation of dust particles. We examine conditions preferred for planetesimal formation in MRI-inactive “dead zones” using an analytic dead-zone model based on our recent resistive MHD simulations. We argue that successful planetesimal formation requires not only a sufficiently large dead zone (which can be produced by tiny dust grains) but also a sufficiently small net vertical magnetic flux (NVF). Although often ignored, the latter condition is indeed important since the NVF strength determines the saturation level of turbulence in MRI-active layers. We show that direct collisional formation of icy planetesimals across the fragmentation barrier is possible when the NVF strength is lower than 10 mG (for the minimum-mass solar nebula model). Formation of rocky planetesimals via the secular gravitational instability is also possible within a similar range of the NVF strength. Our results indicate that the fate of planet formation largely depends on how the NVF is radially transported in the initial disk formation and subsequent disk accretion processes.

Key words: dust, extinction – magnetic fields – magnetohydrodynamics – planets and satellites: formation – protoplanetary disks – turbulence

Online-only material: color figures

1. INTRODUCTION

Formation of kilometer-sized planetesimals is the initial step of planet formation in protoplanetary disks. Several mechanisms have been proposed for planetesimal formation, which include gravitational instability (GI) of dust subdisks (e.g., Goldreich & Ward 1973; Johansen et al. 2007; Youdin 2011) and direct coagulation (e.g., Weidenschilling & Cuzzi 1993; Okuzumi et al. 2012). However, the outcome of these processes strongly depends on the turbulent state of the gas disk. Turbulence is known to concentrate particles of particular sizes, which could assist their gravitational collapse (Cuzzi et al. 2001; Johansen et al. 2007). On the other hand, turbulence also stirs up dust subdisks and thereby stabilizes GI (Turner et al. 2010). In addition, the relative velocity induced by turbulence can lead to catastrophic disruption of large dust particles (Johansen et al. 2008).

The magnetorotational instability (MRI; Balbus & Hawley 1991) has been thought to be the most plausible driving mechanism of protoplanetary disk turbulence. The activity of MRI largely depends on non-ideal MHD effects (e.g., Sano & Miyama 1999; Bai & Stone 2011; Wardle & Salmeron 2012). A high ohmic resistivity creates an MRI-inactive “dead zone” near the midplane (Gammie 1996), which reduces turbulence strength. Importantly, the size of the dead zone depends on the amount of tiny dust particles, because they effectively reduce the gas ionization degree and hence enhance the resistivity (Sano et al. 2000). Although the dead zone has often been invoked as a favorable site for planetesimal formation (e.g., Ciesla 2007; Bai & Stone 2010; Youdin 2011), self-consistent modeling of the MRI–dust coevolution has not been done so far.

Another important, but much less appreciated, factor is the net vertical flux (NVF) of the magnetic fields. The NVF indeed matters since it determines the saturation level of MRI-driven turbulence (e.g., Hawley et al. 1995; Suzuki et al. 2010). This is especially true when a large dead zone is present, in which case the vertically integrated accretion stress decreases with decreasing NVF (Gressel et al. 2012; Okuzumi & Hirose 2011, henceforth OH11).

In this Letter, we investigate possible pathways of planetesimal formation taking into account the dependence of MRI-driven turbulence strength on dust size distribution and NVF strength. In our previous paper (OH11), we systematically studied the saturated state of MRI-driven turbulence with local stratified, ohmic-resistive MHD simulations. We obtained an analytic prescription for the saturation level as a function of the ohmic diffusivity and NVF strength. Using this prescription together with ionization balance calculation including grain charging, we are able to determine turbulence strength consistently with the amount of tiny grains and NVF strength. We consider the formation of rocky and icy planetesimals independently, because icy particles have a high sticking efficiency compared to rocky particles (Chokshi et al. 1993; Gundlach et al. 2011). We test direct collisional formation of icy planetesimals outside the snow line, and rocky planetesimal formation via GI inside the snow line.

2. MODEL DESCRIPTION

We consider a protoplanetary disk around a solar mass star. We take the gas surface density $\Sigma_g$ from the minimum-mass solar nebula (MMSN) model of Hayashi (1981). The gas temperature is taken from the passive, optically thick disk model of Chiang & Goldreich (1997). This model well approximates the gas temperature inside a dead zone, since MRI-driven heating mainly occurs at the upper boundary of the active layer where the optical depth is small (Hirose & Turner 2011). The assumed temperature gives a snow line at orbital radius $r \sim 1$ AU. The gas density $\rho_g$ depends on the distance $z$ from the midplane as $\rho_g = (\Sigma_g / \sqrt{2\pi h}) \exp(-z^2/2h^2)$, where $h$ is the gas scale height given as the sound speed $c_s$ divided by the Keplerian frequency $\Omega$. Because of gas pressure support, the gas disk rotates at a slightly sub-Keplerian velocity. This causes systematic radial
drift of dust particles relative to the mean gas motion. The drift speed reaches the maximum \( |\vec{v}_{g,\text{max}}| \approx 30 \, \text{m s}^{-1} \) when the stopping time \( t_s \) of the particle equals \( \Omega^{-1} \) (Weidenschilling 1977). At \( r \sim 1-5 \, \text{AU} \), the dimensionless stopping time \( t_s \approx 1 \) corresponds to particle radius \( a \sim 1 \, \text{m} \).

We consider MRI-driven turbulence with a dead zone. The most important turbulent quantity for dust evolution is the random velocity of the gas since it determines the collision velocity and diffusion coefficient of dust particles. OH11 found that the gas velocity dispersion at the midplane, \( \delta v_g \), is well approximated as

\[
\delta v_{g,\text{mid}} = \sqrt{0.78 \alpha_{\text{core}} c_s},
\]

where \( \alpha_{\text{core}} \) is the accretion stress integrated over low altitudes and normalized by \( \Sigma c_s^2 \). Equation (1) holds even if the midplane is magnetically dead, since hydrodynamical waves created in active layers propagate across dead-zone boundaries. OH11 also found that \( \alpha_{\text{core}} \) is determined by the dead-zone size and NVF as

\[
\alpha_{\text{core}} = \frac{510}{\beta_{\text{NVF,mid}}} \exp \left( -\frac{0.54 h_{\text{res}}}{h} \right) + 0.011 \exp \left( -\frac{3.6 h_{\text{A}}}{h} \right),
\]

where \( \beta_{\text{NVF,mid}} = 8 \pi \rho_{g,mid} c_s^2 / B_{\text{NVF}}^2 \) is the midplane plasma beta defined by the NVF strength \( B_{\text{NVF}} \), and \( h_{\text{res}} \) and \( h_{\text{A}} \) are quantities that characterize the vertical extent of the dead zone. More precisely, \( h_{\text{res}} \) is the height below which the characteristic MRI wavelength \( \lambda_{\text{res}} = 2 \pi \eta / \nu_{Az} \) in the resistive MHD limit exceeds \( h \), whereas \( h_{\text{A}} \) is the height below which the ohmic Elsasser number \( \Lambda = \nu_{Az} / \eta \Omega \) falls below unity, where \( \nu_{Az} = B_{\text{NVF}} / \sqrt{4 \pi \rho_g} \) is the Alfvén speed defined by the NVF and \( \eta \) is the ohmic diffusivity. Linear stability analysis (Sano & Miyama 1999) shows that ohmic resistivity suppresses the most unstable MRI mode at \( \Lambda \lesssim 1 \) (\( z \lesssim h_{\text{A}} \)) but less unstable modes survive as long as \( \lambda_{\text{res}} \lesssim h \) (\( z \gtrsim h_{\text{res}} \)). Thus, the region \( h_{\text{res}} < z < h_{\text{A}} \) can be interpreted as the transition layer between the active and dead zones. The active layer extends up to \( z = h_{\text{ideal}} \), above which MRI is stabilized because of a low local plasma beta (Sano & Miyama 1999; OH11). In the saturated state, \( h_{\text{ideal}} \) is approximately given by \( h_{\text{ideal}} = [2 \ln(\beta_{\text{NVF,mid}}/3000)]^{1/2} h \) according to the simulations of OH11.

For a given \( \delta v_{g,\text{mid}} \), the gas random velocity \( \delta v_g \) at each height \( z \) is given as \( \delta v_{g} = \exp(z^2/4 h^2) \delta v_{g,\text{mid}} \) (OH11). The vertical diffusion coefficient for dust is given by \( D_z = D_{z,0} / [1 + (\Omega_r t_s)^2] \) (Youdin & Lithwick 2007), where

\[
D_{z,0} \approx \delta v_{g}^2 / 3 \Omega
\]

is the vertical diffusion coefficient for passive (\( \Omega_r \ll 1 \)) contaminants (Fromang & Papaloizou 2006; OH11). Note that Equation (3) applies even in dead zones, which is consistent with the fact that hydrodynamical waves propagating from active layers have a finite correlation time \( \sim \Omega^{-1} \) (Gressel et al. 2012). The turbulence-driven relative velocity \( \Delta v_t \) of dust particles is calculated from the prescription of Ormel & Cuzzi (2007) for Kolmogorov turbulence. In reality, a Kolmogorov energy cascade may not be established for waves in dead zones. However, the assumed \( \Delta v_t \) at least gives a reasonable estimate of the relative velocity for marginally or fully decoupled (\( \Omega_r \gtrsim 1 \)) particles since their relative velocity is determined by the largest-scale gas motion with correlation time \( \sim \Omega^{-1} \) (see Ormel & Cuzzi 2007).

Equations (1) and (2) predict \( \delta v_{g,\text{mid}} \) as a function of \( h_{\text{res}} \), \( h_{\text{A}} \), and \( B_{\text{NVF}} \). We calculate the critical heights by considering the ionization balance at each \( z \), taking into account grain charging. We use the analytic solution of the ionization balance equations derived by Okuzumi (2009), which gives the ionization degree for arbitrary dust size distribution. The ionizing sources we include are Galactic cosmic rays (Umebayashi & Nakano 2009), stellar X-rays (Igea & Glassgold 1999; Bai & Goodman 2009), stellar energetic protons (Turner & Drake 2009), and radionuclides (Umebayashi & Nakano 2009). Inclusion of cosmic and stellar protons gives the minimum estimate of the dead-zone size since strong T-Tauri winds may shield these particles well above disk surfaces. From the ionization balance, we calculate the vertical profile of \( \eta \) (Blaes & Balbus 1994), and obtain \( h_{\text{res}} \) and \( h_{\text{A}} \) for a given \( B_{\text{NVF}} \). Figure 1 plots \( z = h_{\text{res}} \) and \( z = h_{\text{A}} \) versus \( r \) for \( B_{\text{NVF}} = 5 \, \text{mG} \) assuming that 0.1 \( \mu \text{m} \) sized grains are uniformly mixed in the gas with mass abundance \( Z_{\text{small}} = Z_{\text{mid}} / \Sigma_g = 10^{-4} \). Note that the dead-zone size depends on \( B_{\text{NVF}} \); the larger \( B_{\text{NVF}} \) is, the smaller \( h_{\text{res}} \) and \( h_{\text{A}} \) are.

3. ICY PLANETESIMAL FORMATION ACROSS THE FRAGMENTATION BARRIER

Planetesimal formation via direct coagulation is limited by the fact that marginally decoupled (\( \Omega_r \sim 1, a \sim 1 \, \text{m} \)) dust aggregates experience high-speed collisions that can lead to catastrophic disruption (the so-called fragmentation barrier; Brauer et al. 2008). If the disk is laminar, the maximum collision velocity is determined by the differential radial drift velocity \( \sim |\vec{v}_{\text{dr,max}}| \sim 30 \, \text{m s}^{-1} \) (Brauer et al. 2008). Recent numerical collision experiments (Wada et al. 2009) show that aggregates made up of submicron-sized icy grains stick at collision velocities up to \( \sim 50 \, \text{m s}^{-1} \), suggesting that icy planetesimal formation via direct coagulation is possible in laminar disks. However, if the disk has MRI-active layers, a random velocity of \( \sim \delta v_{g,\text{mid}} \) is added to the collision velocity for \( \Omega_r \sim 1 \) aggregates (Ormel & Cuzzi 2007). The question is: can icy aggregates grow across the fragmentation barrier even if the MRI-driven turbulence enhances the collision velocity?
To get a feeling of how the fragmentation barrier depends on dust size distribution and NVF, we begin with a simple two-population model in which large, marginally decoupled ($\Omega_{\text{ts,large}} \sim 1$) aggregates coexist with $0.1 \mu m$ sized small grains. We calculate $\delta v_{\text{g,mid}}$ assuming that only the small grains contribute to the ionization balance. The mass abundance $Z_{\text{small}}$ of the small grains is taken as a free parameter. Figure 2 shows $\delta v_{\text{g,mid}}$ as a function of $Z_{\text{small}}$ for different values of $B_{\text{NVF}}$. For fixed $B_{\text{NVF}}$, $\delta v_{\text{g,mid}}$ increases with decreasing $Z_{\text{small}}$ because the dead zone is smaller when small grains are less abundant. The thick gray line shows $\delta v_{\text{g,mid}} = 38 \text{ m s}^{-1}$; above this line, the total collision velocity for large ($2m_{\text{g}}$, large $\sim 1$) aggregates exceeds the catastrophic disruption threshold for ice (Wada et al. 2009).

(A color version of this figure is available in the online journal.)

4. ROCKY PLANETESIMAL FORMATION
VIA SECULAR GI

Coagulation of rocky aggregates is severely restricted by the fragmentation barrier since the disruption threshold is as low as $1-5 \text{ m s}^{-1}$ (Wada et al. 2009; Gütter et al. 2010). Using that the radial drift speed $|v_{\text{dr}}|$ is approximated as $2|v_{\text{dr, max}}|\Omega_{\text{ts}}$ for $\Omega_{\text{ts}} \ll 1$ (Weidenschilling 1977) and assuming...
that \( v_{\text{dist}} \approx 5 \text{ m s}^{-1} \) and \(|v_{\text{dr}, \text{max}}| \approx 30 \text{ m s}^{-1}\), we find that \(|v_{\text{dr}}|\) reaches \( v_{\text{dist}} \) when \( \Omega_{t_s} \approx 0.08 \), which corresponds to \( a \approx 10 \text{ cm} \) at \( \sim 1 \text{ AU} \). Hence, a simple coagulation scenario does not account for rocky planetesimal formation even without turbulence.

One mechanism that can lead to rocky planetesimal formation is the so-called secular GI (Youdin 2011). It is a gravitational collapse of dust materials driven by the combination of self-gravity and gas friction. An important feature of the secular GI is that it works even if \( \Omega_{t_s} \ll 1 \). Thus, the secular GI can allow gravitational collapse of dust particles whose growth is limited by the fragmentation barrier. Instead, the secular GI requires sufficiently weak radial dust diffusion in order for the particles to collapse faster than they drift inward. For \( \Omega_{t_s} \approx 0.1 \), the radial diffusion coefficient \( D_r \) must be lower than \( 10^{-5} c_s h \) at the midplane (Youdin 2011; Takeuchi & Ida 2012).

To assess whether the secular GI operates for the fragmentation-limited aggregates, we estimate the MRI-driven diffusion coefficient assuming that the aggregates coexist with \( 0.1 \mu \text{m} \) sized fragments of mass abundance \( Z_{\text{small}} \). We also assume that \( D_r \approx D_{r,0} \), which is \( \approx D_{r,0} \) for \( \Omega_{t_s} \approx 0.1 \ll 1 \) (see Equation (3)). Figure 4 shows the midplane radial diffusion coefficient \( D_{r, \text{mid}}(c_s h) \) at 1 AU as a function of \( Z_{\text{small}} \) for different values of \( B_{\text{NVF}} \). We find that \( D_{r, \text{mid}} \) exceeds \( 10^{-5} c_s h \) for \( B_{\text{NVF}} \gtrsim 10 \text{ mG} \) even if \( Z_{\text{small}} \) is as large as the interstellar value \( 10^{-2} \). Thus, the secular GI of the fragmentation-limited aggregates requires \( B_{\text{NVF}} \lesssim 10 \text{ mG} \). This requirement is similar to that for direct icy planetesimal formation shown in Section 3.
5. CONCLUSION AND DISCUSSION

We have investigated how planetesimal formation depends on the amount of tiny grains and the strength of the NVF. For MMSN disks, we have shown that the existence of a large dead zone and an NVF weaker than 10 mG is preferable for planetesimal formation via both direct coagulation and secular GI. The obtained criterion for the NVF depends on the disk surface density \( \Sigma \), since \( \delta v_{g, mid} \propto B_{NVF}/\Sigma^{1/2} \) in the presence of a large dead zone (see Equations (1) and (2)). If \( \Sigma \) is 10 times larger than the MMSN value, then the upper limit on \( B_{NVF} \) goes up to 30 mG.

We have neglected the effects of non-ohmic magnetic diffusivities. Ambipolar diffusion may stabilize MRI near the upper boundary of the active layer (Bai 2011). The effect of Hall diffusion is more uncertain; it can stabilize or destabilize MRI depending on the sign of NVF relative to the disk rotation axis (Wardle & Salmeron 2012). Inclusion of these effects may change our results quantitatively, but the general trend that a weak NVF is preferable might be unchanged.

Weak turbulence is also beneficial to the growth of solid objects larger than planetesimals. Density fluctuations in turbulence gravitationally interact with planetesimal-sized objects and thereby enhance their collision velocity. If MRI is fully active, the resulting gravitational stirring likely causes catastrophic disruption of planetesimals (e.g., Ida et al. 2008; Nelson & Gressel 2010). However, Gressel et al. (2012) have recently shown that even weakly bound planetesimals are able to grow if a dead zone is present and if the NVF is weaker than 3 mG (assuming the MMSN surface density). Thus, a weak NVF and a wide dead zone are preferred for the growth of solid bodies up to protoplanets.

A realistic range of the NVF strength is poorly constrained by direct observations because the differential rotation of the disk can produce toroidal magnetic fields as strong as 0.1–1 G even inside the dead zone (Turner & Sano 2008). An important property of NVF is that the total NVF is a conserved quantity of a magnetized disk. Thus, the total NVF of a protoplanetary disk is directly determined by how the disk formed from weakly magnetized (\( \sim 10 \mu G \); Heiles & Crutcher 2005) molecular clouds. Nevertheless, what fraction of the magnetic flux is brought to the planet-forming inner disk region is not evident because non-ideal MHD processes also work during the disk formation (e.g., Machida et al. 2011). Furthermore, on longer timescales, the NVF may be radially transported due to inward mass accretion (Rothstein & Lovelace 2008) and/or outward macroscopic magnetic diffusion (Lubow et al. 1994) in the active layers. So far, the origin and global transport of NVF has not been given attention in the context of planetesimal formation. We hope that this Letter will encourage further investigation into this issue.

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