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Retention of Small Charged Dust in Planet Forming Disks

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Abstract. Dust evolution in disks around young stars is a key ingredient for the global disk evolution and accompanying planet formation. The mutual sticking of initially small grains is not straightforward and can be hampered by several processes. This includes dust grain bouncing, fragmentation, electrostatic repulsion and fast drift to the central star. In this study we aim at theoretical modeling of the dust coagulation coupled with the dust charging and disk ionization calculations. We show that the electrostatic barrier is a strong restraining factor to the coagulation of micron-size dust. While the sustained turbulence helps to overcome the electrostatic barrier, dust fluffiness limits this opportunity. Coulomb repulsion may keep a significant fraction of $0.1 - 10\mu$m dust in large regions of protoplanetary disks.

Keywords. accretion, accretion disks, plasmas, turbulence, dust, extinction, cosmic rays

1. Introduction

Dust grains in astrophysical environments are not expected to be electrically neutral (Jung 1937, Spitzer 1941). Among a variety of dust charging mechanisms (Weingartner 2004, Fortov *et al.* 2005), plasma charging, i.e. grain collisions with free electrons and ions, is the most important mechanism in dense dark regions of protoplanetary disks. As electrons are more mobile than ions, the equilibrium grain charge is negative in the case of plasma charging. Photoelectric charging can dominate in illuminated disk upper layers and provide positive grain charge. Okuzumi (2009) showed that Coulomb repulsion of like-charged grains can be strong enough to prevent coagulation of micron-size particles in protoplanetary disk environments.

2. Charged dust coagulation

Two key sources of grain relative velocities are the Brownian motion and turbulence. As the Brownian velocities drop with the grain mass and the grain charge linearly scales with grain radius, then the purely Brownian coagulation will be electrostatically blocked for large enough grains ($0.1 - 10\mu$m; Akimkin 2015). Thus, only non-thermal velocities can be responsible for the overcoming of the electrostatic barrier. If the turbulence arises due to the magneto-rotational instability (MRI), its strength should depend on the gas ionization. The MRI is quenched for low ionization degrees $x_{\rm e} < x_{\rm crit} \simeq 10^{-13}$, that diminishes non-thermal grain velocities in a dead zone. The value of $x_{\rm crit}$ is comparable with the abundance of micron-size grains, which can soak up free electrons, so grains play an important role in MRI development. Thus, dust evolution, grain charging and MRI are deeply interrelated processes and must be considered simultaneously.

We model the charged dust evolution by solving Smoluchowski equation locally for a large set of positions in the vertical 2D cut of a protoplanetary disk with

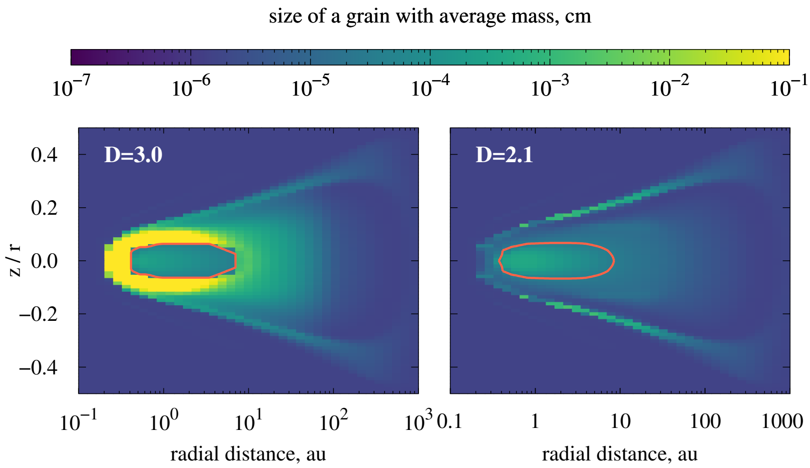

Figure 1. Average grain size a after 10^5 yr of *in situ* dust coagulation for two choices of aggregate fractal dimension $D = 3.0$ and 2.1. Orange solid line shows the location of the dead zone ($\alpha_{\text{dead}} = 10^{-6}, \alpha_{\text{active}} = 10^{-3}$) at 10^5 yr, which we define as a region with low ionization degree. Dust fragmentation, radial drift and sedimentation are not considered. Small average grain sizes ($< 10\mu$m) trace either regions with strong electrostatic barrier (dead zone for $D = 3.0$, almost the whole disk for $D = 2.1$) or just low-density upper and outer disk parts. Macroscopic grain size ($a > 100\mu$m; yellow colour) corresponds to the charge-free coagulation.

typical parameters. The disk charge structure is calculated from the gas recombination-ionization balance with electron depletion and grain charging self-consistently taken into account (Ivlev *et al.* 2016). The considered ionization sources are cosmic rays, X-rays, and radioactive nuclides. The assumed α-parameter is 10^{-3} for the MRI-active disk and 10^{-6} for the dead zone with $x < 10^{-13}$. We do not consider dust fragmentation, radial and vertical drift, which are important for large mm-size dust. We focus on finding the disk regions where strong electrostatic barrier emerges. Coulomb repulsion is important for micron-size dust that does not typically experience strong drift or destructive collisions. On Fig. 1 we show the average grain size after 10^5 yr of dust coagulation for two cases of dust fractal dimension $D = 3.0$ and 2.1. This is actually the map of the severity of electrostatic barrier, it is the strongest in the dead zone for $D = 3.0$ and almost everywhere in the disk for the fractal dust with $D = 2.1$. The zero charge surface is seen as a bright rim in the disk atmosphere.

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