DUST SETTLING IN PROTOSTELLAR ACCRETION DISKS

Dinshaw S. Balsara[1], David A. Tilley[1], Terry Rettig[1] & Sean D. Brittain[2]
[1]*Dept. of Physics, Univ. of Notre Dame, Notre Dame, IN 46556, USA*
[2]*Dept. of Phyics. & Astronomy, Clemson Univ., Clemson, SC 29634, USA*

Introduction: The discovery of extrasolar planets has made planet formation an extremely interesting topic. Observations of disk systems, such as the one in HH30 (Burrows et al. 1996, Cotera et al. 2001) show that the dust seems to have settled into the midplane of the accretion disk. The observed settling of the dust into the midplane of HH30's disk suggests that settling, with subsequent growth of dust, is a critical first step in the process of forming planets. Once coagulation has produced meter or kilometer-sized objects, other collective forces may well play an important role in the formation of planetesimals that eventually form planets. However, that initial settling of dust seems to require an intricate interaction between the dust and gas.

The micro-physics of dust-gas interaction is well-understood. Thus we understand the Epstein and Stokes laws that govern the interaction between small and large dust grains respectively with the gas. It is also well appreciated that TTauri disks need to be turbulent in order to sustain the observed rates of mass accretion on to the central star. Most of the outer parts of such a disk are unstable to magnetorotational instability (MRI) and objections to the MRI existing in the inner parts of such disks seem to be receding (Fatuzzo et al 2006). For that reason, we study the settling of dust spanning a range of dust sizes within MRI-turbulent accretion disks. We study dust sizes spanning seven decades from 0.1 microns to 10 cm. Various types of dust, such as fractal or spherical, can be included in our models and we report on spherical dust grains in this work. The models can also include different dust distributions, representing the effects of dust coagulation, but in this work we consider MRN distributions of dust. A typical protostellar disk can range from the stellar surface out to ~ 300 AU, which is a prohibitive range of radii to simulate. As a result, we design vertically stratified, shearing sheet simulations that are placed at radii of 0.3, 1, 3, 10, 30, 100, 150 and 300 AU and study dust settling in those simulations. The dust settling characteristics vary monotonically with radius, making it possible to interpolate dust properties in radius. The run of disk surface density and temperature were chosen from D'Alessio et al (1998).

The distribution of dust also has utility in forming the disk's SED. The dust absorbs the radiation from the central star and thus sets the disk's temperature. For that reason analytic models for dust settling in turbulent disks have also been presented in the literature (Dubrulle et al 1995, Miyake & Nakagawa 1995). The models suggest that for dust having a size "a", the scale height of the dust to the gas goes as $a^{-1/2}$. We seek to verify that scaling.

Results: Figs. 1a, 1b and 1c show the gas density, z-velocity and y-component of the magnetic field respectively. Figs. 1d, 1e and 1f show the density of dust particles having radii of 0.1 mm, 1 cm and 10 cm. The mid-plane of the simulation is shown and we also show the relevant variables on the outer boundaries of the computational domain. The x,y & z-directions are in the radial, toroidal and vertical directions respectively of the disk. The disk density is stratified in the z-direction. We see that the 0.1 μm dust has a scale height that is comparable to the gas scale height, suggesting that it is well-coupled to the turbulent gas flow. The 1 cm dust has a noticeably smaller scale height, suggesting that it has begun to decouple from the turbulence. The 10 cm dust has decoupled almost completely from the flow and settled in the midplane of the disk. Since the density of this larger dust is substantially greater than its original density and since the rate of coagulation is proportional to the square of the dust density, we see that the larger dust that settles into the midplane will also have an enhanced rate of growth. The 10 cm dust also shows striations, indicative of the formation of a streaming instability in the disk's mid-plane (Youdin & Goodman 2005). The streaming instability develops due to the interaction between the settled large dust and the dominant mode of the MRI and causes the particles to clump into filaments. If the density of large dust is sufficiently high, such a streaming instability can then set the stage for the onset of a gravitational instability (Youdin & Shu 2002).

Fig. 2 shows the ratio of dust to gas scale height as a function of disk's radius for all seven species (sizes) of dust that we evolve in the simulations. We see that the smallest dust tracks the gas scale height at all radii. The 100 μ and 1 mm dust begins to show dust scale heights that are smaller than gas scale height, but this trend only appears at large radii. The 1cm and 10cm dust show very interesting behavior where the dust clearly sediments out into the mid-plane of the accretion disks at exactly the right radii where rocky cores of gas giant planets ought to be forming.

Fig. 3 shows the ratio of dust to gas scale height as a function of grain size for each of the runs that we have simulated. To guide the eye, we also show a dotted line that scales as $a^{-1/2}$, the scaling predicted by theory. We see that the dust to gas ratio is almost unity for very small dust that participates efficiently in the MRI-turbulence. However, larger dust does conform with the theoretical scaling law, building confidence in the simulations and highlighting their utility.

In the results presented above, the dust was represented as particles. It is also possible to represent the different sizes of dust as different species of pressureless fluid that interact with the gas with the appropriate force law. Due to the importance of this problem, we have also formulated it with the dust treated as a continuum. We find that for small dust, where the dust attains its terminal velocity in a short distance, the two formulations agree. For larger dust, a particulate formulation has an advantage because it allows the dust to develop a random velocity in the disk's midplane, yielding bigger dust scale heights.

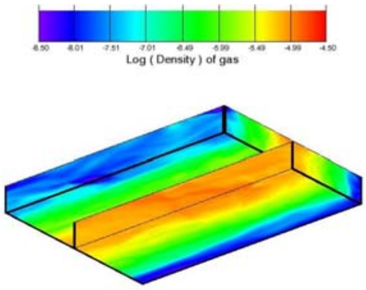


Fig. 1a

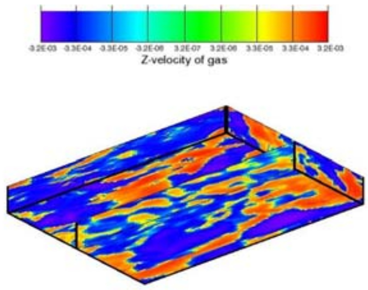


Fig. 1b

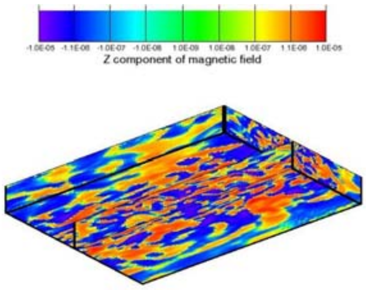


Fig. 1c

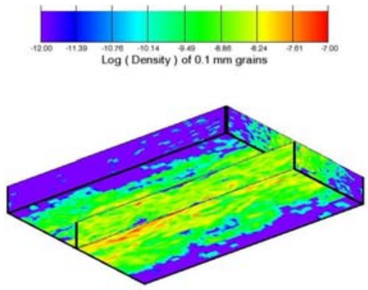
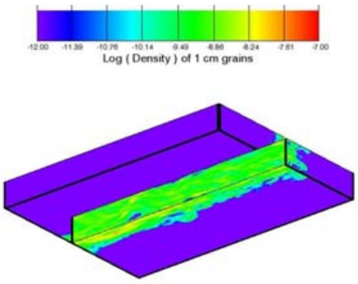
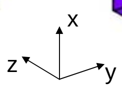


Fig. 1d





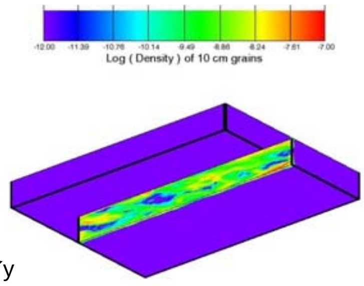


Fig. 1e

Fig. 1f

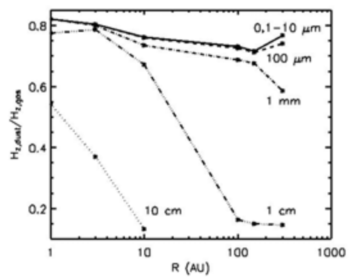


Fig. 2

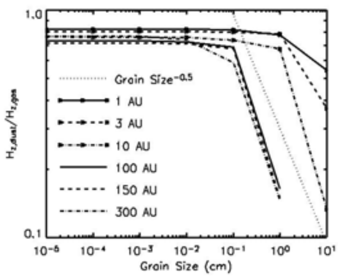


Fig. 3

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