GAS-DRAG INDUCED MIGRATION OF SOLIDS IN THE VICINITY OF A DENSITY ENHANCEMENT IN A NON-UNIFORM SOLAR NEBULA.

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We present the results of an extensive numerical study of the orbital evolution of small solids, ranging from dust grains to km-sized objects, in the vicinity of a local density enhancement in a non-uniform solar nebula. In a previous study we have shown that when the motions of such solids are restricted to the midplane of the nebula, the combined effect of gas drag and pressure gradients causes the solids to radially migrate toward the location of the maximum gas density. In this paper, we extend our previous analysis to three-dimensional cases and show that such migrations can occur along both radial and vertical directions. We also show that for a certain range of solids' radii, these migrations can be quite rapid. The implications of such rapid migrations for collisional coagulations of small solids and also for enhancement of the growth-rate of planetesimals are also discussed.

Motivation

It is widely accepted that formation of planets starts with collision and coalescence of small solids in a circumstellar disk. Study of the collisional growth of such solids is of utmost of importance since it furthers our understanding of the early stages of planet formation processes.

It has recently been noted that a planet-forming nebula may be gravitationally unstable[1]. In such an unstable rotating gaseous disk, the pressure of the gas does not change monotonically with distance and it maximizes at certain locations[2,3]. The pressure gradients of the gas in such a nebula, necessary for maintaining its hydrostatic equilibrium, become negative at distances beyond the location of the maximum pressure and become positive at closer distances. This, combined with the drag force of the gas, causes solids at large distances to feel a headwind and migrate inward and those at closer distances to experience a tailwind and migrate outward. Such migrations are fundamentally important since they have immediate implications on the collisions and coagulations of small bodies and can consequently enhance the growth-rate of planetesimals. This has motived us to launch an extensive systematic numerical study of the orbital evolution of small solids in gravitationally unstable nebulae and to investigate the possibility of their collisional coagulation.

In a previous paper [4], we studied the gas-drag induced migration of solids, ranging from dust grains to kilometer-sized objects, in the neighborhood of pressure-enhanced regions of a non-uniform nebula. The results of our two-dimensional numerical simulations of the motion of solids, restricted to the midplane of the nebula, indicated that such solids tend to radially migrate toward the locations where the density of the nebular gas maximizes. In this paper we extend our previous study to three-dimensional cases in which solid objects can also move along the vertical axis. We show that in this case, solids rapidly migrate toward the midplane while they also undergo radial migration. We also study how the rates of such migrations are affected by the size and density of solids and also the temperature of the gas.

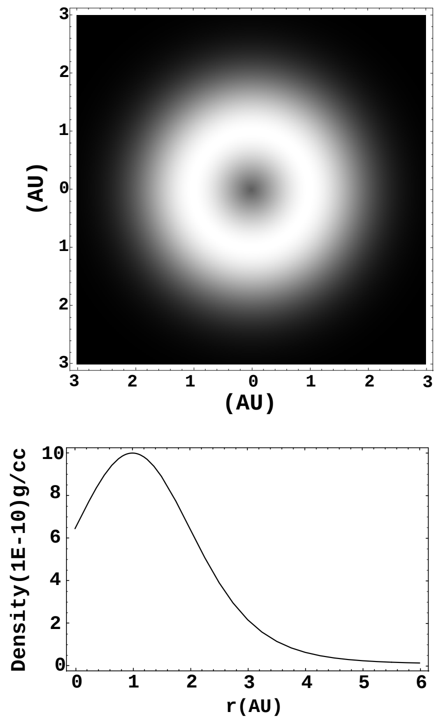

Figure 1.

Physical Model

We consider a turbulence-free, isothermal rotating gaseous nebula of pure molecular hydrogen with a Sun-like star at its center. In order to focus attention on the radial and vertical migrations of solids, the density of the gas has been chosen such that on its midplane, it has an azimuthally symmetric maximum (figure 1). For such a nebula, the z-dependence of the gas density is

Gas-Drag Induced Migration of Small Solids in a Non-Uniform Nebula

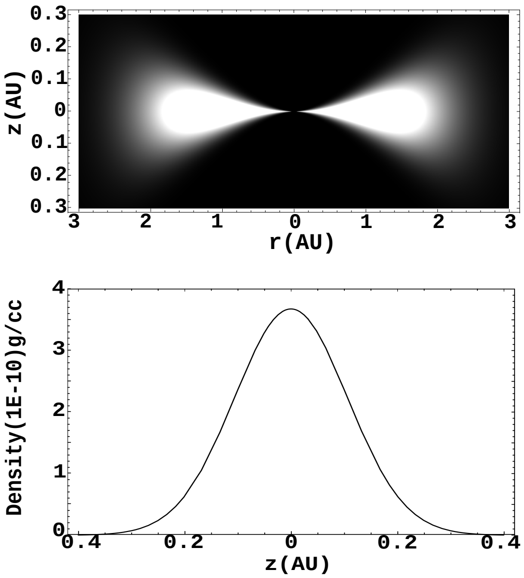

Figure 2.

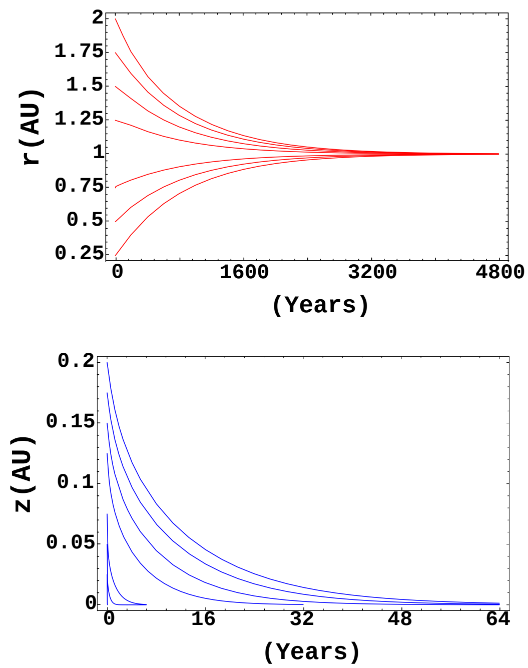

Figure 3

derived from balancing the z-component of the gravitational attraction of the central star with the vertical component of the pressure gradient. The scale height of our model nebula is one-tenth of the radial distance at any location (figure 2).

Since molecular hydrogen is an ideal gas, in such a nebula, locations of density enhancements correspond to the locations of maximum pressure. We have simulated the motions of solids subject to the gravitational attraction of the central star and also the drag force of the gas, for different values of solids' radii and densities and also for different values of the gas temperature, on both sides of density enhancements. Because the drag force of the gas has different functional forms for different values of the solids' radii, we have adopted the formula presented by Supulver and Lin [5] which combines the Stokes and Epstein regimes in one equation. The results of a sample run are presented below.

Numerical Results

We integrated the equation of motion of solids with radii ranging from 1 micron to 1 kilometer for a nebula with the density shown in figures 1 and 2. The density of solids were varied between 1 to 5 gcm^{-3} and the temperature of the gas ranged from 25 to 1000 K. Figure 3 shows the results of such simulations for a 10 cm solid with a density of 2 gcm^{-3} in a nebula with a temperature equal to 300 K. Solids were initially placed on both sides of $r = 1$ AU and at a height equal to one-tenth of their radial distances. They were given an initial Keplerian circular velocity parallel to the midplane and zero initial velocity along the vertical axis. As shown in figure 3, such solids undergo vertical and radial migrations. They rapidly approach the midplane of the nebula where, as shown in figure 2, the density of the gas has its local enhancement along the z-axis. At the same time, they radially migrate toward $r = 1$ AU where from figure 1, the gas density is maximized on the midplane.

Rapid migration of a 10 cm solid is a familiar result that was also observed in our two-dimensional simulations. In fact, the rate of migration varies with the size and the physical properties of solids and the gas in such a way that the most rapid migrations are observed among centimeter to meter-sized objects. We present the results of our comprehensive numerical study for different solids' sizes and densities as well as different values of the gas temperature. We also show how interactions among solids such as their collision and coalescence will affect the rate of their migrations.

References

[1] Inaba S., and Wetherill G. W., 2002, Talk presented at the Frontiers in Scientific Research on Extrasolar Planets Conference. [2] Boss A., 2000, ApJ, **536**, L101. [3] Mayer L., Quinn T., Wadsley J., and Stadel J., 2002, Science, **298**, 1756. [4] Haghighipour N., and Boss A. P., to Appear in ApJ February 1, 2003. Also see LPSC 2002, abstract 1376. [5] Supulver K.D. and Lin D.N.C., 2000, Icarus, **146**, 525.