Particle-Gas Dynamics in the Protoplanetary Nebula

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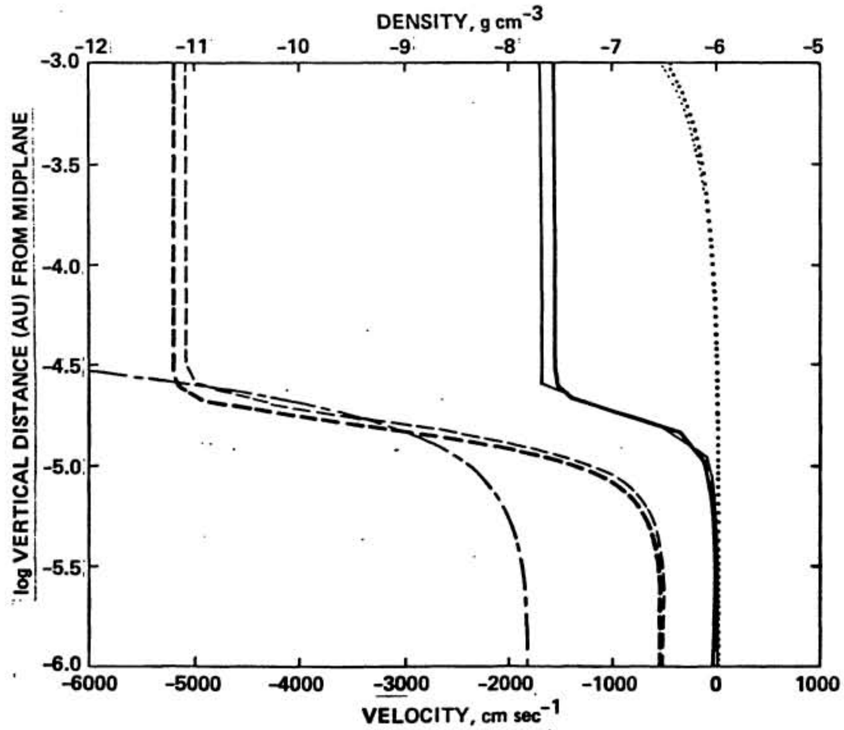
Current scientific consensus is that flattened disks of dust and gas, with constrained global thermal and dynamical properties, will form as a natural byproduct of stellar formation. Accumulation of grains into comet-sized planetesimals, and subsequently the growth of solid planetary cores by collisional accretion of planetesimals (e.g. [1]), is followed (in the outer solar system) by rapid accretion of nebula gas to form Jovian-type planets (e.g. [2]). However, poorly understood stages connect these landmark events. For instance, it is often assumed that the earliest particulates settle quickly into a sufficiently flattened layer that gravitational instability may occur [3], rapidly producing planetesimal-sized objects. However, shear-driven turbulence in and around the particle layer may result in *diffusion*, not collapse, of a layer of small but macroscopic particles, preventing gravitational instability [4]. In addition, the body of meteorite data is replete with examples of non-equilibrium mineralogy, and peculiar grain sizes and shapes, which appear to be indications of accretionary processes active among small but macroscopic particles in the protoplanetary nebula which are not seen anywhere else in the geological record (e.g. [5]).

To better understand this earliest stage of particle growth in the nebula, we have initiated detailed numerical modeling of the early nebula environment which carefully treats the processes occurring in a medium containing two distinct phases (gas and particles) which obey different forcing functions but are coupled by aerodynamic drag, thereby influencing each other's dynamical properties. We have been developing our model in stages, drawing on existing expertise in state-of-the-art computational fluid dynamics techniques and particle disk dynamics.

At present, we have developed a two-dimensional numerical model which solves for the two-phase dynamical behavior of a radially narrow annulus of the gas-particle protoplanetary nebula. Our code uses a perturbation technique and several different parametrizations for the turbulence which have been successfully used in many similar situations in the past. We have compared it with prior analytical solutions in the inviscid (laminar) limit [6], with excellent agreement. The nebula gas, in general, is partly pressure-supported so that it orbits at a slightly slower rate than the particles. This causes isolated particles to suffer a size-dependent "headwind" [7], which affects their orbital evolution. However, as the particles settle towards the midplane under gravity, their density begins to dominate. As the mass-dominant particles drive the locally intermingled gas towards their own (higher) orbital velocity, the "headwind" nearly vanishes while significant vertical wind shear is produced relative to the more slowly rotating pressure-supported gas above the particle layer.

Prior inviscid models are unable to model the effects of turbulence at all, let alone in a fully self-consistent way. Our models use standard parametrizations of shear-driven turbulence to obtain the "turbulent" or "eddy" viscosity of the gas phase. Determining the subsequent diffusive transport of the particles requires introduction of a nondimensional "Schmidt number", which depends on the fluctuation timescales of the turbulence and the "stopping time" of the particles (a function of their mass and size). We have begun to explore reasonable ranges of Schmidt number (constrained by prior aerodynamical experience). We will present preliminary results on the potential for turbulence to diffusively expand the particle layer and prevent gravitational instability.

Other interesting aspects of the coupled behavior of the gas-particle system include a radial flow in the gas in the vicinity of the particle layer caused by momentum transfer between the particle layer and the intermingled gas. We are currently exploring all of these issues in greater detail.



Comparison of our numerical results (heavy lines) for the mean particle velocities, relative to Keplerian velocity and in the absense of turbulence, with the analytical (laminar) model of Nakagawa et al. [6] (light lines). A typical minimum mass nebula is assumed with midplane gas density 1.3×10^{-9} g cm^{-3}. Solid: radial velocity; dashed: azimuthal velocity; dotted: vertical velocity; dash-dot: particle density profile. Note that the particle layer is about 10^{-4} of the thickness of the gaseous nebula.

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