A numerical turbulence model for multiphase flows in the protoplanetary nebula

Joëlle M. Champney
Applied and Theoretical Mechanics, Inc., Palo Alto, California 94306

Anthony R. Dobrovolskis
University of California, Santa Cruz, California 95064

Jeffrey N. Cuzzi
NASA-Ames Research Center, Moffett Field, California 94035-1000

(Received 18 March 1994; accepted 6 March 1995)

It is thought that planets form from solid particles in a flattened, rotating, 99% gaseous nebula. These grains gradually coagulate into millimeter-to-meter sized aggregates which settle toward the midplane of the nebula. It is widely believed that the resulting dense layer eventually becomes gravitationally unstable and collapses into “planetesimals.” A new numerical model is presented to simulate the predominant processes (gravitation, vertical convection, and shear-driven turbulence) during the stage while the particulate material is still dispersed about the midplane of the nebula. In our previous work, particles were assumed to be spheres of a single radius; in the present work, particles are spheres of different radii. Results indicate that neither a broad nor a narrow distribution of particle sizes is likely to become gravitationally unstable. © 1995 American Institute of Physics.

I. INTRODUCTION

Dense regions of interstellar clouds collapse under their own gravity into young stars, surrounded by flattened disks of dusty gas.\(^1\) Our own Solar system presumably originated from such a protoplanetary nebula. Subsequent collisions of asteroid-like “planetesimals” (followed by hydrodynamic capture of gas in the outer Solar nebula) led to their accretion into planets.

The solid component of the nebula initially consisted of microscopic grains well-mixed with the gas. These grains would gradually coagulate into millimeter-to-meter sized aggregates, which then settle into a thin layer at the central plane of the disk due to the vertical component of the Sun’s gravity.\(^2,3\) It is widely believed\(^4,5\) that as its density increases, this layer eventually grows gravitationally unstable and collapses directly into planetesimals. The criterion for gravitational instability may be written as

\[
p_p > M/(\pi R^3),
\]

where \(p_p\) is the bulk density of solid particles, \(M\) is the mass of the Sun, and \(R\) is the distance from the Sun.\(^6\)

In recent years, however, it has become clear that planetesimals must form by other means, because settling of solid particles is a self-limiting process.\(^2,3,7,8\) A radial pressure gradient causes the gaseous disk to rotate at slightly less than the Kepler orbital velocity. In contrast, the particle-rich layer is not supported by pressure, and so tends toward Keplerian motion. The resulting shear between the particle layer and the surrounding gas generates turbulence that stirs particles back into the nebula and reduces their bulk density below the stability limit.

In order to simulate this situation, we have developed a computational fluid dynamics (CFD) model for multiphase flow in which the protoplanetary nebula is treated as a mixture of gas molecules and solid particles. The temporal and spatial evolution of the mixture is described by the Reynolds-averaged Navier–Stokes equations for each phase. The gas eddy viscosity is obtained from a Prandtl turbulence model adapted to the nebula flows of interest. The particle diffusivity is modeled by means of a Schmidt number expressed as a function of particle size and density.

Our initial results, presented in Cuzzi et al.,\(^8\) confirm that particles of a given mass and radius settle into a stable distribution about the midplane. In general, the lighter the particles, the thicker the layer. An interesting loophole remains, though. If particles of different sizes coexist, it is possible that the lighter particles may spread into such a thick layer that shear is reduced and turbulence is suppressed. Then the heavier particles could settle into a dense sublayer, which might become gravitationally unstable after all.

The goal of the present work is to examine this possibility by including particles of different sizes and compositions simultaneously. Our mathematical model is described in Sec. II, divided into six subsections detailing our assumptions, the model nebula, the governing equations, the perturbation technique, the Reynolds averaging method, and the turbulence model used to close the system. Section III describes the numerical technique, while Sec. IV presents the results.

II. MATHEMATICAL MODEL

A. Assumptions

The assumptions used in modeling the protoplanetary nebula are outlined below. The gas phase is assumed to be a perfect gas, known to be predominantly hydrogen. The solid phases are each assumed to consist of spherical particles of a fixed mass and radius. Each phase is treated as a continuum. Momentum is exchanged between the gas and particle phases by means of the drag force. Each particle phase is independent of the other particle phases; they interact only through the intermediary of the gas phase. The settling of...
particles is modeled by taking into account turbulence generated in the gas by the presence of the particles. Collisions among particles are not taken into account, so the model is valid only for dilute suspensions; however, it contains no limitation on the mass loading ratio. The mean flow is assumed axisymmetric ($\partial \overline{\theta} = 0$) and isothermal. Brownian effects on the particle phase are neglected, as well as electromagnetic forces. The self-gravity of the nebula is also neglected. Cuzzi et al.\(^8\) demonstrate that this assumption is valid as long as condition (1) is not close to being satisfied.

B. Nebula model

The physical characteristics of the protoplanetary nebula are now introduced. A standard "minimum mass" circumstellar nebula is assumed with total mass 0.0425 $M_\odot$. The surface density $\sigma(r)$ of the disk is of the form

$$\sigma(r) = \sigma_0 (r/\text{AU})^{-1.5},$$  \hspace{1cm} (2)

where AU represents 1 astronomical unit (1.49x10\(^{13}\) cm). This leads to a surface mass density $\sigma_0 = 1700$ g cm\(^{-2}\) at $r = 1$ AU.

The disk is also assumed vertically isothermal at temperature

$$T(r) = T_0 (r/\text{AU})^{-0.5},$$  \hspace{1cm} (3)

where $T_0 = 280$ K. Because this is too warm for water ice to precipitate, the condensible mass fraction of $5.3 \times 10^{-3}$ gives the solid particles a surface mass density of about 9 g cm\(^{-2}\) at 1 AU.

Equations (2) and (3) above imply a gas density

$$\rho_g(r,z) = \rho_{\text{ref}} (r/\text{AU})^{-11/4} \exp[-(z/z_G)^2],$$  \hspace{1cm} (4)

where $z_G$ is called the scale height. Note $z_G$ is always much greater than the depth of the particle layer, so the variation of gas density with height can be neglected. For example, $z_G = 8 \times 10^6$ km at $r = 1$ AU in the baseline model. The gas density $\rho_{\text{ref}}$ at 1 AU is $1.4 \times 10^{-9}$ g cm\(^{-3}\). The corresponding molecular mean free path is about 1 cm, so most of the particles are in the Stokes drag regime.

C. Governing equations

The equations describing the Solar nebula are expressed in a cylindrical coordinate system ($r$, $\theta$, $z$) as

1. **Gas phase**:

   For gas phase, the governing equations are:
   
   \begin{align*}
   \frac{\partial}{\partial t} \rho_g + \frac{1}{r} \frac{\partial}{\partial r} \left( r \rho_g u_r \right) + \frac{\partial}{\partial z} \left( \rho_g u_z \right) &= 0, \\
   \frac{\partial}{\partial t} u_r + u_r \frac{\partial}{\partial r} u_r + u_z \frac{\partial}{\partial z} u_r + \frac{1}{\rho_g} \frac{\partial P}{\partial r} &= \frac{u_r^2}{r} - \frac{GM}{R^2} - \sum_{p=1}^{n} A_p\rho_p(u_r-u_p), \\
   \frac{\partial}{\partial t} u_z + u_r \frac{\partial}{\partial r} u_z + u_z \frac{\partial}{\partial z} u_z + \frac{1}{\rho_g} \frac{\partial P}{\partial z} &= \frac{u_z^2}{r} - \frac{GM}{R^2} \sum_{p=1}^{n} A_p\rho_p(u_z-u_p) + \frac{1}{\rho_g} \frac{\partial}{\partial r} \left( r \tau_{rr} \right) - \frac{\tau_{g\theta}}{\rho_g} + \frac{1}{\rho_g} \frac{\partial}{\partial z} \frac{\partial \tau_{rz}}{\partial z},
   \end{align*}

   where $t$ is time, $\rho$ is density, and $P$ is pressure. Here $u_r$, $u_z$, and $u$ respectively are the components of velocity in the radial, $\theta$ (circumferential), and $z$ (vertical) directions. The subscripts $g$ and $p$ refer to the gas phase and particle phases, respectively. Here $n$ is the number of distinct particle sizes; $n$ is limited only by available computer resources; $G$ is the gravitational constant, equal to $6.7 \times 10^{-8}$ cm$^3$ g$^{-1}$ s$^{-2}$. Thus the vertical and radial components of the Sun's gravitational attraction become $GM/2R^2$ and $GM/2R^3$, respectively. Finally $\tau_{ij}$ is the molecular stress tensor expressed in cylindrical coordinates, equal to $\tau_{ij} = \mu (u_{ij} + u_{ji})$, where $\mu = 0.001$ g/cm/s is the gas molecular viscosity. Equation (12) is presented in conservative form for reasons given in Sec. III.

2. **Particle phase**:

   For the particle phase, the governing equations are:
   
   \begin{align*}
   \frac{\partial}{\partial t} \rho_p + \frac{1}{r} \frac{\partial}{\partial r} \left( r \rho_p u_r \right) + \frac{\partial}{\partial z} \left( \rho_p u_z \right) &= \frac{1}{\rho_p} \frac{\partial}{\partial r} \left( r \tau_{pr} \right) - \frac{\tau_{p\theta}}{\rho_p} + \frac{1}{\rho_p} \frac{\partial}{\partial z} \frac{\partial \tau_{pz}}{\partial z}, \\
   \frac{\partial}{\partial t} u_r + u_r \frac{\partial}{\partial r} u_r + u_z \frac{\partial}{\partial z} u_r - \frac{\tau_{g\theta}}{\rho_p} + \frac{1}{\rho_p} \frac{\partial}{\partial r} \left( r \tau_{rr} \right) &= \frac{u_r^2}{r} - \frac{GM}{R^2} \sum_{p=1}^{n} A_p\rho_p(u_r-u_p), \\
   \frac{\partial}{\partial t} u_z + u_r \frac{\partial}{\partial r} u_z + u_z \frac{\partial}{\partial z} u_z &= \frac{u_z^2}{r} - \frac{GM}{R^2} \sum_{p=1}^{n} A_p\rho_p(u_z-u_p) + \frac{1}{\rho_p} \frac{\partial}{\partial r} \left( r \tau_{zr} \right) - \frac{\tau_{gz}}{\rho_p} + \frac{1}{\rho_p} \frac{\partial}{\partial z} \frac{\partial \tau_{gz}}{\partial z},
   \end{align*}

   where $t$ is time, $\rho$ is density, and $P$ is pressure. Here $u_r$, $u_z$, and $u$ respectively are the components of velocity in the radial, $\theta$ (circumferential), and $z$ (vertical) directions. The subscripts $g$ and $p$ refer to the gas phase and particle phases, respectively. Here $n$ is the number of distinct particle sizes; $n$ is limited only by available computer resources; $G$ is the gravitational constant, equal to $6.7 \times 10^{-8}$ cm$^3$ g$^{-1}$ s$^{-2}$. Thus the vertical and radial components of the Sun's gravitational attraction become $GM/2R^2$ and $GM/2R^3$, respectively. Finally $\tau_{ij}$ is the molecular stress tensor expressed in cylindrical coordinates, equal to $\tau_{ij} = \mu (u_{ij} + u_{ji})$, where $\mu = 0.001$ g/cm/s is the gas molecular viscosity. Equation (12) is presented in conservative form for reasons given in Sec. III.

The drag coefficient can be expressed as $A_p = (\rho_p c_p)^{-1}$ (Ref.8), where $t_p$ is the particle response time and depends on the ratio of the particle radius $r_p$ to the mean free path $\lambda_g$ of a gas molecule. For $r_p \leq \frac{\lambda_g}{2}$ (Epstein flow regime),

$$t_p = \frac{\rho_s r_p}{\rho_g c_p}.$$  \hspace{1cm} (13)

Here $\rho_s$ is the density of an individual solid particle, and $c$ is the speed of sound in the gas. For $r_p > \frac{\lambda_g}{2}$ (Stokes flow regime),
\[ I_p = \frac{8}{3} \frac{\rho_r}{\rho_g} \frac{r_p}{C_D (v_p - v_g)} \]  

where \( C_D \) is the drag coefficient:

\[ C_D = 24 \frac{1}{R_e} \] for \( R_e < 1 \),
\[ C_D = 24 \frac{1}{R_e^{0.6}} \] for \( 1 < R_e < 800 \),
\[ C_D = 0.44 \] for \( R_e > 800 \).

Here \( R_e \) is the Reynolds number
\[ R_e = \frac{2 \rho_r r_p}{\mu |v_p - v_g|} \]
where \( |v_p - v_g| \) is the magnitude of the relative velocity between the particle phase and the gas.

### D. Perturbation technique

Because we are interested in relatively small variations of physical quantities over large distance ranges, it is appropriate to solve the preceding set of equations in a perturbed form. The equations are expanded about a reference state as shown below. We seek a solution such that:

\[ u_g = u, \quad v = v_0 + v_1, \quad w = w, \quad \rho_g = \rho_g + \rho_1, \quad p = p_0 + p_1, \quad T = T_0, \]
\[ u_p = u_{p1}, \quad v_p = v_{p0} + v_{p1}, \quad w_p = w_{p1}, \quad \rho_g = \rho_{g1}. \]

Substitution of this expansion in the exact equations leads to the following equations at zero order:

\[ \frac{\partial \rho_0}{\partial t} = 0, \]
\[ \frac{\partial \rho_0 u_0}{\partial r} = \rho_0 \frac{v_0^2}{r} - \frac{\rho_0 G M r}{R^2} \] (local centrifugal balance),
\[ \frac{\partial \rho_0}{\partial z} = - \frac{\rho_0 G M z}{R^2} \] (hydrostatic approximation),
\[ \frac{\partial v_0}{\partial t} = 0, \]
\[ \frac{v_{p0}^2}{r} = \frac{G M r}{R^2} \] (Keplerian motion).

We choose
\[ \rho_0 = \rho_0 R_g T_0 / m, \quad v_0 = v_K, \quad v_K = r \Omega_K, \]
\[ \Omega_K^2 = G M / R^3, \quad v_0 = v_K[1 - \eta]^{1/2}, \]
\[ \eta = - \frac{r}{2 v_K} \frac{\partial P_0}{\partial r} \ll 1. \]

Here \( R_g \) is the gas constant \((8.3143 \times 10^7 \text{ erg/K/mole})\) and \( m \) is the mean molecular weight of the gas \((2.34 \text{ amu})\). The quantity \( v_K \) is the Keplerian orbital speed, and \( \eta \) is the fractional deviation of the gas from Keplerian rotation \( \text{(proportional to the radial pressure gradient)} \). To first order, the perturbed state will satisfy the following equations in their exact form:

\[ \frac{\partial}{\partial t} \rho_1 + \frac{1}{r} \frac{\partial}{\partial r} \left[r (\rho_0 + \rho_1) u_1 \right] + \frac{\partial}{\partial z} \left[(\rho_0 + \rho_1) w_1 \right] = 0. \]  

E. Reynolds averaging

The perturbation quantities themselves are further expanded into means and variations, in the usual notation:

\[ \rho' = \rho - \bar{\rho}, \quad u = \bar{u} + u', \quad v = \bar{v} + v', \quad w = \bar{w} + w'. \]

By definition, variation quantities vanish on the average:

\[ \rho' = 0, \quad u' = 0, \quad v' = 0, \quad w' = 0, \quad \text{etc.} \]

This form is substituted into the perturbation equations (23)-(30), which are then time averaged (Reynolds averaged) over an interval short compared to the evolution of the nebula but long compared to the time scales of the turbulence.

Originally, we solved the vertical gas momentum equation (8) for \( \bar{w} \), the mean value of the gas vertical velocity perturbation. However, the Courant–Friedrichs–Lewy (CFL) condition required a very small time step for Eq. (8) to be numerically stable. We soon found that neglecting \( \bar{w} \) eliminated the need for this CFL condition, and the time step could be increased an order of magnitude. Since \( \bar{w} \) was always small, setting \( \bar{w} = 0 \) made no noticeable difference in the results.

Since the gas density \( \rho_g \) is nearly constant, its fluctuation will be very small, and any correlation involving \( \rho_g' \) is neglected. In the simulations presented in this paper, radial gradients \( (\partial/\partial r) \) of perturbation quantities are also neglected by scaling. The resulting set of equations is shown below in the form in which they are solved. The overbar sign on all mean variables has been eliminated for clarity:

\[ \frac{\partial}{\partial t} \rho + \frac{\partial}{\partial z} \left[ (\rho_0 + \rho) w \right] = 0, \quad (31) \]

\[ \frac{\partial u}{\partial t} + \frac{\partial u}{\partial z} = \frac{\rho_0 (\rho_0 + \rho)}{\rho_0} \frac{\partial P_0}{\partial r} + \frac{2 u v_0 + u^2}{r} \frac{\partial z}{\partial \theta} - \frac{T_{\theta\theta}}{\rho_0 + \rho} r + \frac{1}{\rho_0 + \rho} \frac{\partial}{\partial z} \tau_{e}^{r} - \sum_{p=1}^{n} A_p \rho_p (u - \bar{u}_p), \quad (32) \]

\[ \frac{\partial v}{\partial t} + \frac{\partial v}{\partial z} = -u \frac{\partial v_0}{\partial r} - \frac{\partial v_0}{\partial z} \frac{u (u + v)}{r} + \frac{T_{\theta z}}{\rho_0 + \rho} + \frac{1}{\rho_0 + \rho} \frac{\partial}{\partial z} T_{\theta z} - \sum_{p=1}^{n} A_p \rho_p (v_0 + v - \bar{v}_p), \quad (33) \]

\[ w = 0, \quad (34) \]

\[ \frac{\partial}{\partial t} \rho_p + \frac{\partial}{\partial z} (\rho_p w_p + \rho_p' w_p') = 0, \quad (35) \]

\[ \frac{\partial u_p}{\partial t} + \frac{\partial u_p}{\partial z} = \frac{2 u v_{p0} + u_p^2}{r} \frac{\partial z}{\partial \theta} + \frac{T_{p \theta}}{\rho_p} + \frac{1}{\rho_p} \frac{\partial}{\partial z} T_{p z} - \frac{\rho_p' w_p'}{\rho_p} \frac{\partial u_p}{\partial z} - A_p (\rho_0 + \rho) (u_p - \bar{u}_p), \quad (36) \]

F. Turbulence modeling

To close the system of equations, we adopted the formulation of Cuzzi et al., summarized as follows. Applying the Prandtl mixing length model to nebula flows, we express the turbulent eddy viscosity \( \mu_i \) as the square of a mixing length times the local gas density and vorticity:

\[ \mu_i = (c_i \delta)^2 \rho_k \sqrt{\left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2}. \quad (41) \]

Here we take the mixing length equal to a constant \( \delta = 0.045 \) times the boundary layer thickness \( \delta = 0.02 \eta v_k / \Omega_k \).
Correlations between particle density and particle veloc-
ity are specified according to the gradient diffusion hypoth-
esis. Since the particle density gradient is dominated by its
vertical component, this implies

$$\rho_p \nabla \rho_p \theta = 0, \quad \rho_p \nabla \rho_p \phi = 0, \quad \rho_p \nabla \rho_p \psi = - \frac{\mu_t}{S_c \rho_p} \frac{\partial}{\partial z} \rho_p.$$

(42)

Here $S_c$ is the Schmidt number, given by

$$S_c = (1 + S_t) \sqrt{1 + 3 \frac{w^2}{2 k}},$$

(43)

where $S_t = \Omega K t_p$ is called the particle Stokes number, and $t_p = \left( \frac{A_p \rho_p}{\mu_t} \right)^{-1}$ is the time constant of the drag.$^8$ The turbulent kinetic energy $k$ is obtained from the eddy viscosity $\mu_t$ through the relation

$$\mu_t = \frac{C_{\mu}^2}{R_0} \frac{k}{\Omega K},$$

(44)

where $R_0$ is the critical Rossby number (empirically set to
80) and $C_{\mu}$ is a dimensionless coefficient (set to 0.09; Ref. 8).

Correlations between particle density and gas velocity
are taken approximately equal to the corresponding particle-
particle correlations. Consequently, the drag term involving
the difference $(\rho_p \nabla \rho_p \phi - \rho_p \nabla \rho_p \psi)$ cancels out of Eq. (38) for
the vertical momentum of the particles.

III. NUMERICAL TECHNIQUE

A. Algorithm

The multiphase flow code is an extension of the two-
phase flow code, with all particle variables expressed as ar-
rays to take into account the different sizes of particles. The
code employs dimensional variables, expressed in CGS
units, but this can easily be changed. In this code, the time-
dependent Navier–Stokes equations (31)–(38) are solved us-
ing a time-marching approach. Time-dependent methods are
commonly used in Computational Fluid Dynamics applica-
tions to obtain a steady-state numerical solution of a fluid
flow. By their use, a boundary-value problem is transformed
into an initial-boundary value problem with unknown initial
data (see Yee, Ref. 9, p. 127), for which efficient algorithms
can be used.

Implicit algorithms to solve partial differential equations
with stiff source terms, like those in this paper, are still at the
development stage (see Yee, Ref. 9, p. 118). Because our
goal is to obtain a numerical solution to an as-yet unsolved
problem, we use a well-developed explicit algorithm. We
selected the 1969 MacCormack scheme,$^{10}$ because it has
widely been used in aerodynamical simulations, although it
has not been applied to astrophysical problems until this
work.$^7$ We refer the reader to the work of Mendez-Nunez
and Carroll,$^{11,12}$ who recently evaluated the MacCormack al-
gorithm for atmospheric problems and demonstrated its ad-

tantages with respect to numerical stability, diffusion, and
dispersion.

The radial and azimuthal momentum equations (32),
(33), (36), and (37) are solved in nonconservative form. This
form is employed instead of the more common conservative
form in order to minimize roundoff errors in the particle
velocities. In the conservative form, such errors may arise
when the conservative variables $\rho_p \nabla \rho_p \theta, \rho_p \nabla \rho_p \phi, \rho_p \nabla \rho_p \psi$ are di-
vided by the density $\rho_p$ to obtain the primitive variables
$u_p, v_p, w_p$. With the nonconservative form, this is avoided
since we solve directly for the primitive variables.

However, we encountered a problem with the particle
vertical momentum equation. Because of the terms containing $\rho_p w_p$ which originated from averaging advection terms, the conservative form (38) is actually more stable. In the one-dimensional case treated here, the particle continuity equation (35) and vertical momentum equation (38) are strongly coupled to each other, but coupled to the other two particle momentum equations (36) and (37) only through the value of the turbulent viscosity $\mu_t$. Because of this situation, we have adopted a hybrid solution scheme. We solve (35) and (38) simultaneously in conservative form using first-order, upwind differencing for the advective terms (sacrificing some accuracy for the sake of stability), and second-order central differencing for the viscous terms. Then $\rho_p$ and $w_p$ are updated to the next time step, and the gas and particle radial and azimuthal momentum equations are solved in non-conservative form.

Although this approach was stable, the algorithm tended to lose particle mass, due to excessive numerical diffusion arising from the first-order spatial differencing. Sophisticated numerical techniques that conserve particle (or species) mass to machine accuracy have been designed for unsteady multidimensional aerosol problems, in particular by Toon et al.\textsuperscript{13} However, because we are looking for the steady-state solution, a simpler approach was employed to conserve particle mass.

We periodically applied an integrodifferential correction to compensate for the loss of particle mass. In a steady state, $\partial \rho_p / \partial t = 0$, so that the particle continuity equation (35) and formula (42) give

$$\tilde{\rho}_p \tilde{w}_p + \tilde{\rho}_p \tilde{w}_p = \tilde{\rho}_p \tilde{w}_p = C = \tilde{\rho}_p \tilde{w}_p - \frac{\mu_t}{\rho_g} \frac{\partial \rho_p}{\partial z},$$

(45)

where $C$ is a constant. Evaluating the left side of Eq. (45) above at $z=0$ gives $C=0$, while integrating it leads to

$$\tilde{\rho}_p(z) = \tilde{\rho}_p(0) \exp \left( \int_0^z \frac{S_c \rho_g}{\mu_t} \tilde{w}_p \, dz \right).$$

(46)

In the numerical model, the value of $\tilde{\rho}_p(0)$ is determined from the total initial particle mass, and the profile of $\tilde{\rho}_p(z)$ is updated at each time step from Eq. (46) above. This technique was found to be quite successful.

B. Boundary conditions

Our code was designed to treat flow in both the vertical and radial directions. Because so little is known about the particle settling, though, we have thus far restricted ourselves to one-dimensional calculations. Since the largest gradients lie in the vertical direction, we have neglected the complication of radial flow for the time being. Accordingly, we define the numerical grid with either 102 or 202 rows in the vertical direction, but only three columns (IE=3) in the radial direction. This geometry is depicted in Fig. 1. Zero-gradient conditions are imposed at both radial boundaries $l=1$ and $l=3$, so that all dependent variables are the same in each vertical column. Similar conditions are imposed on the horizontal rows $K=1$ and $K=3$, corresponding to symmetry across the midplane at $K=2$.  

FIG. 3. Similar to Fig. 2, but all particles are 10 cm in radius. Note change in scales.

FIG. 4. Similar to Fig. 3, but for the 60 cm particles in a nebula containing equal masses of particles 10 and 60 cm in radius. Note change in scales.

---

Champney, Dobrovolskis, and Cuzzi
IV. RESULTS

Our first results are described below. The flow is a mixture of solid particles of individual density $\rho_s = 1.0$ g/cm$^3$ with nebular gas at $r = 1$ AU where the temperature is 280 K. Initially, the mesh consisted of 102 points with a vertical resolution of 600 km and a time step of 1/2 hour. After 11 years of evolution, the mesh was refined by linear interpolation to 202 points with a vertical resolution of 300 km, and restarted with a time step of 1/4 hour. This resolution is still ~100 times larger than the smallest eddies, and the time step is orders of 10 longer than their turnover time. In each case, the multiphase flow runs extend over about 13 years of simulated time, requiring about 2 hours of CPU time on a Cray Y-MP. Over the duration of the runs, residuals dropped by more than 4 orders of magnitude, indicating good convergence toward a steady-state solution.

The results of these simulations are shown in Figs. 2–4. Figure 2 represents a two-phase run in which all particles were 60 cm in radius, while Fig. 3 displays a similar case where all particles were 10 cm in radius. These cases were selected because of the contrast in the thickness of the particle layers. For comparison, Figs. 4 and 5 present a multiphase flow containing equal masses of both species; Fig. 4 refers to the particles of radius 60 cm while Fig. 5 applies to those of radius 10 cm. The total mass of all particles was the same in every run.

The dot–dashed curves in each figure plot the bulk density $\rho_p$ of the particle cloud; the scale is shown at the bottom of the upper panel. The solid and dashed curves in the lower
terminal velocity. Speed of the small particles continually adjusts to the local momentum. In contrast, because particles falling from higher levels retain some momentum, the particle density gradient, $s$. The good agreement between the particle velocity, measured with respect to the Keplerian speed $u_K$ (bottom scale). The corresponding gas velocities $u$ and $v$ are shown in the upper panel (labeled “G”), relative to pressure-supported circular motion $v_0$ (top scale).

The light dotted line in the lower panel represents the particle vertical velocity $w_p$. The heavy dashed curve is the diffusion velocity

$$w_{\text{diff}} = \frac{\rho_p w_p^2}{\mu_T} \frac{1}{s_c} \frac{\partial \rho_p}{\partial z},$$ \hspace{1cm} (48)

defined as the effective velocity of the mass flow driven by the particle density gradient. The good agreement between $w_{\text{diff}}$ and $w_p$ in the dense particle layer indicates that the particles are not settling appreciably.

The heavy dotted curve plots the terminal velocity $w_F$, the speed of fall for which the particle's weight is balanced by drag:

$$w_F = -\frac{GM}{R^3} \frac{z}{A \rho_0} = -\Omega_K^2 z t_p(z).$$ \hspace{1cm} (49)

For the 60 cm particles of Figs. 2 and 4, $w_F$ differs from $w_p$ because particles falling from higher levels retain some momentum. In contrast, $w_F$ is indistinguishable from $w_p$ for the 10 cm particles of Figs. 3 and 5, indicating that the falling speed of the small particles continually adjusts to the local terminal velocity.

Note that the particle density profile $\rho_p$ is much thicker in the 10 cm case (Fig. 3) than in the 60 cm run (Fig. 2). This is due to the greater diffusivity of the smaller particles. As a result, the profiles of azimuthal velocity $v$ and $u_p$ are also thicker in Fig. 3 than in Fig. 2. Overall, the results of the multiphase simulations (Figs. 4 and 5) are fairly similar to the results of the two-phase runs (Figs. 2 and 3). As expected, the velocity gradient in the multiphase case is intermediate between that in the two unimodal cases. This actually causes the 10 cm particles in Fig. 5 to settle into a thinner layer than in Fig. 3. However, the distribution of 60 cm particles in Fig. 4 is no denser than that in Fig. 2. This indicates that more realistic models including a broad distribution of particle sizes are not likely to be less stable in the Goldreich–Ward sense.

In Fig. 4, we also observe numerical oscillations in the radial velocity $u_p$ of the 60 cm particles that were not present in the two-phase flow computations. We verified that these oscillations are reduced with a finer mesh, confirming that they are of numerical origin, and caused by our unwillingness to use an artificial viscosity.

Note in each figure that drag between the particle-rich layer and the surrounding particle-poor nebula causes a radial outflow of the gas. This outflow $u$ peaks at $\sim$5,000 km above the midplane in Fig. 2, and at $\sim$30,000 km in Fig. 3, just above the respective particle-rich layers. In the multiphase case, however, we observe two maxima in $u$ corresponding to both particle sublayers. This effect could have significant implications for the radial transport of small particles in the protoplanetary nebula and the compositional inhomogeneity of planetesimals.

Finally, we extended the multiphase run from 13 years to 51 years of simulated time. Lack of time and resources prevented us from optimizing the time step, so we simply increased it by a factor of 10 and restarted the run. The results, displayed in Figs. 6 and 7, are practically indistinguishable from those at 13 years plotted in Figs. 4 and 5. This demonstrates that a steady state has indeed been reached.

ACKNOWLEDGMENTS

The first author dedicates this paper to the memory of her husband Philip D'Arcy Champney, who was so enthusiastic and supportive of her research endeavor. We also thank Dr. Thomas Coakley, Dr. Stuart Weidenschilling, and two anonymous referees for their comments and suggestions. Dr. Brian Toon also provided helpful suggestions and some support to complete this paper. This research was funded by NASA's Planetary Geology and Geophysics and Origins of Solar Systems programs. The Numerical Aerodynamic Simulator program of NASA's Office of Aeronautics supplied computational support.


