

# Streaming Instability Code Comparison Problem Set

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## 1 INTRODUCTION

The streaming instability is a promising mechanism to drive planetesimal formation. Since its discovery (Youdin & Goodman 2005), several hydrodynamics codes have explored the parameters, non-linear properties, and implications of this aerodynamic instability that requires feedback between dust and gas momenta. However, the non-trivial differences between numerical techniques (e.g., finite difference or finite volume) and dust modeling (e.g., as a pressureless fluid or as Lagrangian particles) can make it difficult to disentangle unique scientific results from the potential idiosyncrasies of a particular code or implementation. In an effort to address these issues, this collaborative project aims to comprehensively compare various multipurpose codes across some of the key models and problems previously studied in investigations into the streaming instability.

### 1.1 Repositories

#### 1.1.1 Project and source files

Project and source files related to this project can be found in the associated [GitHub repository](#). [JUPYTER NOTEBOOKS](#) containing [PYTHON](#) scripts to generate the manuscript figures can be found in the [/ipynb](#) directory. Source and input files for some participating codes, as well as pseudo code for particular models, can be found in the [/source\\_files](#) directory. To be consistent with the structure of this document (Section 1.2), the subdirectories therein are hierarchically organized first by *model*, next by *problem*, next by *variation*, and last by *code*. For more information, please see the repository [README](#), and feel free to [create an issue](#) for any questions, feedback, or issues encountered.

#### 1.1.2 Output data

The problem data outputted by participating codes should be uploaded to the designated [Google Shared Drive](#). To be consistent with the structure of this document (Section 1.2), the subdirectories therein are hierarchically organized first by *model*, next by *problem*, next by *variation*, and last by *code*. Regardless of the inherent data format normally generated by a participating code, all requested output (e.g., arrays) must be stored in or converted to individual compressed [NUMPY](#) [.npz](#) files (see the official “[Input and output](#)” [documentation](#) for details).

The [.npz](#) files should be named and structured as follows. To verify setup consistency between codes and compliance with specified parameters, simulation snapshots for each problem and variation must be accompanied by a [grid.npz](#) file containing the cell-centered

coordinates in separate arrays for each axes using the keyword arguments (`**kwargs`) `x`, `y`, and/or `z`. The snapshots themselves should be named as the corresponding simulation time without leading zeros, with the initial snapshot at  $t_{\text{sim}} = 0$  named `0.npz`. The requested quantities within each snapshot should be stored in individual arrays using the keyword arguments specified by each problem or variation (e.g., `rho` for the particle density). Time series data should be saved as `time_series.npz` and contain individual arrays with the keyword arguments `time` (for the corresponding simulation times) and those specified by each problem or variation for the requested quantities (e.g., `maxrho` for the maximum particle density). The requested cadence (i.e. time increment between outputs  $dt$ ) for the time series is also specified by each problem or variation. All quantities, including times and coordinates, should be saved in the units specified by each problem, as detailed in later sections (Section 1.2).

### 1.2 Document structure

The subsequent structure of this document is as follows. The sections themselves (e.g., Section 2) correspond to particular *models* with different source terms (e.g., unstratified vs. stratified). Within each section, the first subsection (e.g., Subsection 2.1) explains the setup and relevant quantities for the corresponding model. The second subsection (e.g., Subsection 2.2) identifies the specific *problems* of interest, the relevant *variations* of parameter values, and the corresponding objectives for the code comparison.

## 2 UNSTRATIFIED

As detailed in [Baronett et al. \(2024, sec. 2\)](#), the unstratified problems are modeled without the vertical component of stellar gravity in the local-shearing-box approximation ([Goldreich & Lynden-Bell 1965](#)), where the equations of motion are linearised with Cartesian `x`, `y`, and `z` axes constantly aligned to the radial, azimuthal, and vertical directions, respectively. The Keplerian reference frame is axisymmetric with periodic boundary conditions in all directions. Pseudo-code for this model that implements the gas and dust source terms detailed in Section 2.1 can be found in the GitHub repository in the [/source\\_files/unstratified](#) directory (Section 1.1.1).

## 2.1 Model setup

### 2.1.1 Gas

From [Baronett et al. \(2024, sec. 2.1\)](#), the continuity and momentum equations for the inviscid gas ( $\nu = 0$ ) are

$$\frac{\partial \rho_g}{\partial t} + \nabla \cdot (\rho_g \mathbf{u}) = 0, \quad (1)$$

$$\begin{aligned} & \frac{\partial \rho_g \mathbf{u}}{\partial t} + \nabla \cdot (\rho_g \mathbf{u} \mathbf{u} + P \mathbf{I}) \\ &= \rho_g \left[ 2\Omega_K u_y \hat{\mathbf{x}} - \frac{1}{2} \Omega_K u_x \hat{\mathbf{y}} + 2\Omega_K \Pi c_s \hat{\mathbf{x}} - \frac{\rho_p}{\rho_g} \left( \frac{\mathbf{u} - \mathbf{v}}{t_{\text{stop}}} \right) \right], \end{aligned} \quad (2)$$

respectively. Solving for the gas density  $\rho_g$ , the gas velocity  $\mathbf{u}$  is measured relative to the background Keplerian shear flow  $\mathbf{u}' = -(3/2)\Omega_K x \hat{\mathbf{y}}$ , where  $\Omega_K$  is the local Keplerian angular frequency. In equation (2),  $P = \rho_g c_s^2$  for an isothermal equation of state with speed of sound  $c_s$ , and  $\mathbf{I}$  is the identity matrix. The first two source terms on the right-hand side of equation (2) are a combination of the radial component of the stellar gravity and the Coriolis and the centrifugal forces. The third term is a constant outward force on the gas due to an external radial pressure gradient, determined by the dimensionless parameter ([Bai & Stone 2010, eq. 1](#))

$$\Pi \equiv \frac{\eta v_K}{c_s} = \frac{\eta r}{H_g} = 0.05, \quad (3)$$

where  $v_K$  is the local Keplerian velocity,  $H_g = c_s/\Omega_K$  is the vertical gas scale height, and

$$\eta \equiv -\frac{1}{2} \frac{1}{\rho_g \Omega_K^2 r} \frac{\partial P}{\partial r} = -\frac{1}{2} \left( \frac{H_g}{r} \right)^2 \frac{\partial \ln P}{\partial \ln r} \sim \left( \frac{c_s}{v_K} \right)^2, \quad (4)$$

is the fractional reduction in orbital speed of the gas from Keplerian (when  $\eta > 0$ ) if the dust were not present ([Nakagawa et al. 1986, eq. 1.9](#)). The fourth and final term is the frictional drag force from the solid particles back to the gas, where  $\mathbf{v}$  is the ensemble-averaged local velocity of the particles (measured relative to the background shear) and  $t_{\text{stop}}$  is their stopping time. The factor of the dust-to-gas density ratio  $\rho_p/\rho_g$  ensures the conservation of the total linear momentum of the gas and dust particles, where  $\rho_p$  is the spatially averaged dust density in the gas cell.

The gas density field is initially uniform with  $\rho_g(x, y, z, t = 0) = \rho_{g,0}$ . By assuming a total dust-to-gas mass ratio

$$\epsilon \equiv \frac{\langle \rho_p \rangle}{\rho_{g,0}}, \quad (5)$$

where

$$\langle f \rangle \equiv \frac{1}{L_x L_y L_z} \iiint f dx dy dz \quad (6)$$

is the instantaneous volume average of quantity  $f$  over the computational domain of dimensions  $L_x \times L_y \times L_z$ , the initial components of the gas velocity take the equilibrium solution by [Nakagawa et al. \(1986\)](#):

$$u_{x,0} = -\epsilon v_{x,0}, \quad (7)$$

$$u_{y,0} = -\left[ 1 + \frac{\epsilon \tau_s^2}{(1 + \epsilon)^2 + \tau_s^2} \right] \frac{\eta v_K}{1 + \epsilon}, \quad (8)$$

$$u_{z,0} = 0, \quad (9)$$

where

$$\tau_s \equiv \Omega_K t_{\text{stop}}. \quad (10)$$

is the dimensionless stopping time (a.k.a. Stokes number; [Youdin & Goodman 2005](#)).

### 2.1.2 Lagrangian dust particles

From [Baronett et al. \(2024, sec. 2.2\)](#), the dust is modeled as Lagrangian super-particles, each of which represents an ensemble of numerous identical solid particles described by their total mass and average velocity. The equations of motion for the  $i$ -th super-particle is then

$$\frac{d\mathbf{x}_{p,i}}{dt} = \mathbf{v}_i - \frac{3}{2} \Omega_K x_{p,i} \hat{\mathbf{y}}, \quad (11)$$

$$\frac{d\mathbf{v}_i}{dt} = 2\Omega_K v_{i,y} \hat{\mathbf{x}} - \frac{1}{2} \Omega_K v_{i,x} \hat{\mathbf{y}} - \frac{\mathbf{v}_i - \mathbf{u}}{t_{\text{stop}}}, \quad (12)$$

where the velocity  $\mathbf{v}_i$  is measured relative to the background Keplerian shear  $\mathbf{v}'_i = -(3/2)\Omega_K x_{p,i} \hat{\mathbf{y}}$ . The right-hand side of equation (12) parallels equation (2) in Lagrangian form without the radial gas pressure gradient. The gas velocity  $\mathbf{u}$  is interpolated at the particle position  $\mathbf{x}_{p,i}$  using the Triangular-Shaped-Cloud scheme under the standard particle-mesh method ([Hockney & Eastwood 1981](#)). For a monodisperse population of dust, the stopping times  $t_{\text{stop}}$  and  $\tau_s$  (equation 10) are the same for all particles. As with the gas (equations 7–9), the initial components of the particle velocity take the equilibrium solution by [Nakagawa et al. \(1986\)](#):

$$v_{i,x,0} = -\left[ \frac{2\tau_s}{(1 + \epsilon)^2 + \tau_s^2} \right] \eta v_K, \quad (13)$$

$$v_{i,y,0} = -\left[ 1 - \frac{\tau_s^2}{(1 + \epsilon)^2 + \tau_s^2} \right] \frac{\eta v_K}{1 + \epsilon}, \quad (14)$$

$$v_{i,z,0} = 0. \quad (15)$$

### 2.1.3 Pressureless dust fluid

From [Youdin & Johansen \(2007, sec. 2.1.1\)](#), the continuity and momentum equations for the inviscid ( $\nu = 0$ ) and pressureless dust fluid are

$$\frac{\partial \rho_d}{\partial t} + \nabla \cdot (\rho_d \mathbf{v}) = 0, \quad (16)$$

$$\begin{aligned} & \frac{\partial \rho_d \mathbf{v}}{\partial t} + \nabla \cdot (\rho_d \mathbf{v} \mathbf{v} + P \mathbf{I}) \\ &= \rho_d \left[ 2\Omega_K v_y \hat{\mathbf{x}} - \frac{1}{2} \Omega_K v_x \hat{\mathbf{y}} - \frac{1}{\rho_d} \left( \frac{\mathbf{v} - \mathbf{u}}{t_{\text{stop}}} \right) \right], \end{aligned} \quad (17)$$

respectively. Solving for the dust density  $\rho_d$ , the dust velocity  $\mathbf{v}$  is measured relative to the background Keplerian shear flow  $\mathbf{v}' = -(3/2)\Omega_K x \hat{\mathbf{y}}$ . The right-hand side of equation (17) parallels equation (2) without the radial gas pressure gradient. As with the gas (equations 7–9), the initial components of the dust velocity take the equilibrium solution by [Nakagawa et al. \(1986\)](#):

$$v_{x,0} = -\left[ \frac{2\tau_s}{(1 + \epsilon)^2 + \tau_s^2} \right] \eta v_K, \quad (18)$$

$$v_{y,0} = -\left[ 1 - \frac{\tau_s^2}{(1 + \epsilon)^2 + \tau_s^2} \right] \frac{\eta v_K}{1 + \epsilon}, \quad (19)$$

$$v_{z,0} = 0. \quad (20)$$

## 2.2 Problems

As in [Johansen & Youdin \(2007\)](#), the problems below are intended to study the non-linear saturation of the streaming instability. The

**Table 1.** Parameters for the unstratified problems, the different dust implementations, and their variations (Section 2.2). The columns are (1) problem name, (2) dimensionless stopping time<sup>a</sup>, (3) total dust-to-gas mass ratio<sup>b</sup>, (4) domain size, (5) snapshot times, (6) snapshot keywords, (7) time series cadence, (8) time series keywords, (9) average number of Lagrangian particles per cell  $n_p$  or Gaussian velocity noise  $dv$ , and (10) grid resolution. Length, time, and density are in units of gas scale height  $H_g$ , orbital period  $T^c$ , and initially uniform gas density  $\rho_{g,0}$ , respectively.

Problem	$\tau_s$	$\epsilon$	$L_x = L_y = L_z$ ( $H_g$ )	Snapshots $t_{\text{sim}}/T$	keywords	Time series $dt/T$	keywords	Dust	$N_x \times N_y \times N_z$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
BA	1.0	0.2	2.0	0, 5, 10, 20, 50, 100	rhop	0.1	maxrhop	$n_p = 1$	$512 \times 1 \times 512$
								$n_p = 1$	$1024 \times 1 \times 1024$
								$n_p = 9$	$512 \times 1 \times 512$
								$dv = 0.01 c_s$	$512 \times 1 \times 512$
								$dv = 0.01 c_s$	$1024 \times 1 \times 1024$

<sup>a</sup> Defined by equation (10)

<sup>b</sup> Defined by equation (5)

<sup>c</sup> Defined by equation (21)

parameter values for the following problems, the different dust implementations, and their associated variations are summarized in Table 1.

### 2.2.1 BA

This problem and its associated variations are based on run “BA” from Johansen & Youdin (2007). As key parameters,  $\tau_s = 1.0$ , and  $\epsilon = 0.2$ . The domain size is  $L_x \times L_y \times L_z = 2 H_g \times 2 H_g \times 2 H_g$  (Section 2.1.1).

Output data should include simulation snapshots and a time series (Section 1.1.2). The grid coordinates should be in units of the vertical gas scale height  $H_g$ . The snapshots should be taken at  $t_{\text{sim}}/T = 0, 5, 10, 20, 50$ , and  $100$ , where

$$T \equiv 2\pi/\Omega_K, \quad (21)$$

is the local orbital period. These should contain dust density field in units of the initially uniform gas density, i.e.  $\rho_p(x/H_g, z/H_g)/\rho_{g,0}$  (Section 2.1.1), stored with the keyword argument `rhop`. The time series should include the maximum particle density in the domain in units of the initially uniform gas density, i.e.  $\max(\rho_p)/\rho_{g,0}$ , stored with the keyword argument `maxrhop` at a cadence of  $dt = 0.1T$ .

For simulations that implement Lagrangian dust particles, the requested dust density quantities should be mapped onto the gas grid via the particle–mesh assignment (Section 2.1.2). The first two variations should use a total number of particles, which are randomly distributed throughout the domain, such that there are  $n_p = 1$  particles per cell on average. For  $n_p = 1$ , the first and second variations should have grid resolutions of  $N_x \times N_y \times N_z = 512 \times 1 \times 512$  and  $1024 \times 1 \times 1024$ , respectively. The third variation should have  $n_p = 9$  with  $N_x \times N_y \times N_z = 512 \times 1 \times 512$ .

Simulations that implement a pressureless dust fluid (Section 2.1.3) should initially perturb the fluid with Gaussian noise at 1% of the sound speed for all velocities, i.e.  $dv = 0.01 c_s$ . The first and second variations for this implementation should have resolutions of  $N_x \times N_y \times N_z = 512 \times 1 \times 512$  and  $1024 \times 1 \times 1024$ , respectively

The parameter values for the different dust implementations and their associated variations are included in Table 1. Code comparison objectives for this problem and its variations include comparing morphologies, maximum density evolution, and cumulative distribution functions.

## REFERENCES

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## APPENDIX A: PENDING

The following sections are works in progress, some of which may be included in the main text above in future revisions of this document.

## APPENDIX B: UNSTRATIFIED

### B1 Problems

#### B1.1 AB

Unstratified monodisperse streaming instability. This is run “AB” of Johansen & Youdin (2007).

The box should have dimensions  $L_x = L_z = 0.1H \times 0.1H$ , resolution is  $1024 \times 1024$ , Stokes number  $St = 0.1$ , dust-to-gas ratio  $\epsilon = 1$ , number of particles: 4 particle per cell (4,194,304 particles).

20 snapshots taken between 0 and 2 (on intervals of 0.1) orbits and single snapshots at 3 and 4 orbits (units of  $2\pi/\Omega$ ). Snapshots should contain densities and velocities for the gas and particles, as well as the particle positions (can be separate snapshots).

Submit the results as numpy savez files (.npz), containing, respectively

- (i) a file with the grid arrays,  $x$  and  $z$
- (ii) files with the particle density for each snapshot;
- (iii) the particle positions for each snapshot;
- (iv) time series (with  $dt = 0.01$  orbits), containing the time and the particle and gas density and velocity dispersions, as defined by equations 10 and 11 of Baronett et al. (2024, sec. 3.1).

*Objective: compare dispersions, cumulative distribution function, and morphological evolution.*

*B1.2 lin A*

Linear, unstratified monodisperse streaming instability. This is run “lin A” of Youdin & Johansen (2007).

TO DO

*Objective: reduce non-linearity of initial conditions, identify close to pure code comparisons.*

**APPENDIX C: STRATIFIED****C1 2D***C1.1 Lagrangian dust particles*

Clumping threshold for streaming instability. This is run Z0.4t30 of Li & Youdin (2021).

The box should have dimensions  $L_x = L_z = 0.8H \times 0.4H$ , resolution is  $1024 \times 512$ , Stokes number  $St = 0.3$ , dust-to-gas ratio  $Z = 0.01$ .

Number of particles should be 4 particles per cell, but considering the effective particle scale height ( $H_p \approx 0.1H \approx 2\eta r$ ). For  $\Pi = 0.05$ , that’s 262,144 particles.

Vertical boundary condition: reflective (zero normal velocity  $u_z$ , zero gradient for  $u_x$  and  $u_y$ ).

Initial condition: Gaussian for gas density, particles settled with particle scale height  $H_p = 0.025$ .

Snapshots taken at 5, 10, 20, 50, 100 orbits (units of  $2\pi/\Omega$ ). Snapshots should contain particle density and particle positions. Time series of maximum particle density.

*Objective: Do codes agree on clumping?*

*C1.2 Pressureless dust fluid*

Same as Problem 3A but for fluid. Start fluid with Gaussian noise at 1% of sound speed for all velocities.

**C2 3D**

3D Streaming Instability. This is a 3D extension of Problem 4A (with higher  $Z$  also, for shorter computation time).

The box should have dimensions  $L_x = L_z = 0.8H \times 0.4H \times 0.4H$ , resolution is  $1024 \times 512 \times 512$ , Stokes number  $St = 0.3$ , dust-to-gas ratio  $Z = 0.01$ , number of particles:  $N_w \times \Pi = 13,421,772$ .

Vertical boundary condition: reflective (zero normal velocity  $u_z$ , zero gradient for  $u_x$  and  $u_y$ ).

Initial condition: Gaussian for gas density, particles settled with particle scale height  $H_p = 0.025$ .

Midplane and vertical slice of particle density at 2, 5, 10, and 20 orbits. Full datacube at 20 orbits (units of  $2\pi/\Omega$ ). Snapshots should contain particle density and particle positions. Time series of maximum particle density.

This paper has been typeset from a  $\text{\TeX}/\text{\LaTeX}$  file prepared by the author.