PLUTO: A NUMERICAL CODE FOR COMPUTATIONAL ASTROPHYSICS

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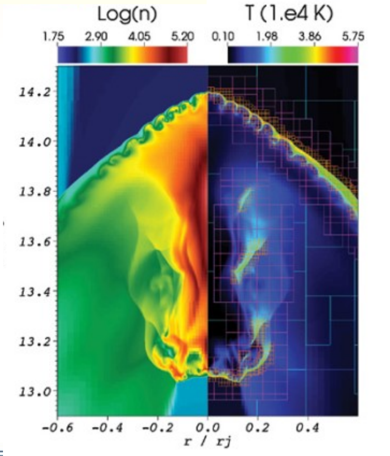
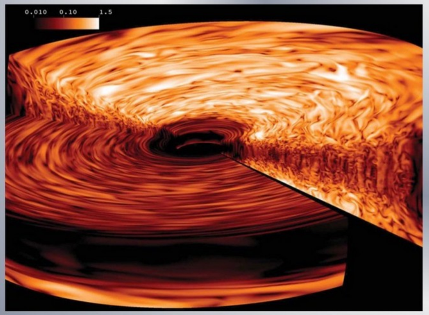
Institute for Advanced Studies in Basic Sciences (IASBS)

Workshop on computational astrophysical fluids

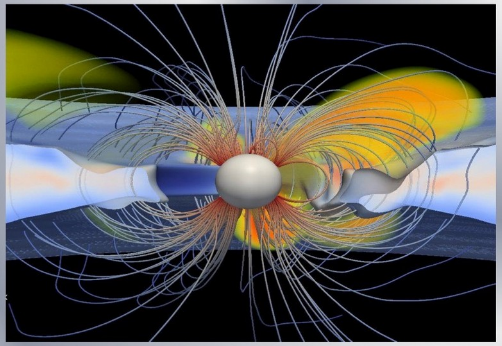
IPM – April 2025 (Ordibehesht 1404)

Radiative shocks

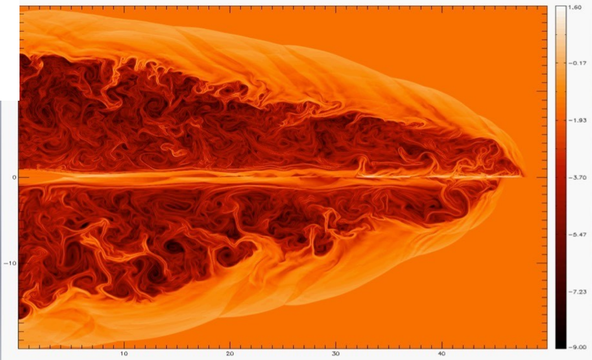




Turbulent r.m.s. velocity field in a 3D magnetized accretion disk. Flock et al., ApJ (2011) 735



MHD modeling of flares occurring in young stellar objects (YSOs) with the aim to investigate the effects of the flares on the stability of the circumstellar disk surrounding the central protostar, Orlando et al., MNRAS (2011) 415, 3380.



Magnetic field strength in a 2D axisymmetric relativistic magnetized jet at the resolution of 40 zones per jet radius (R=1). The figure compares the results obtained with the HLLD solver (upper half) with the HLL solver (lower half), see Mignone et al, MNRAS (2009) 393, 1141.

Institute for Advanced Studies in Basic Sciences
Gava Zang, Zanjan, Iran

PLUTO: A NUMERICAL CODE FOR COMPUTATIONAL ASTROPHYSICS

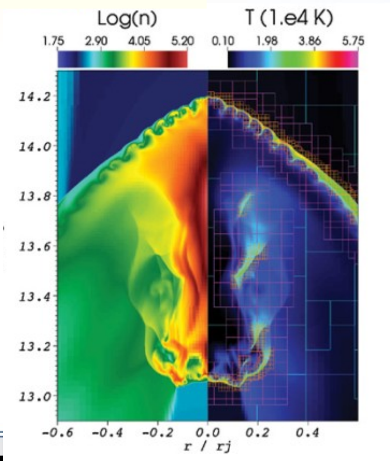
PLUTO v. 4.4-patch3 (September 2024)

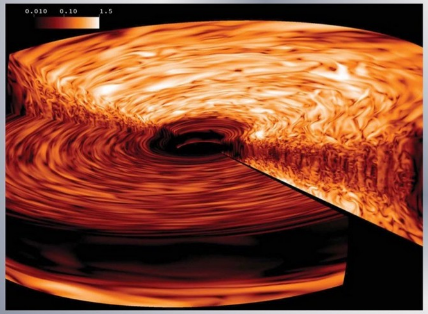
User's Guide https://plutocode.ph.unito.it/

Mignone et al. ApJS (2007), 170, 228-242;

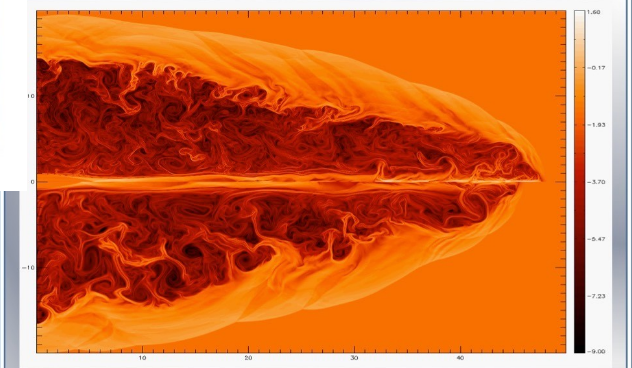
Mignone et al, ApJS (2012), 198, 7

Radiative shocks

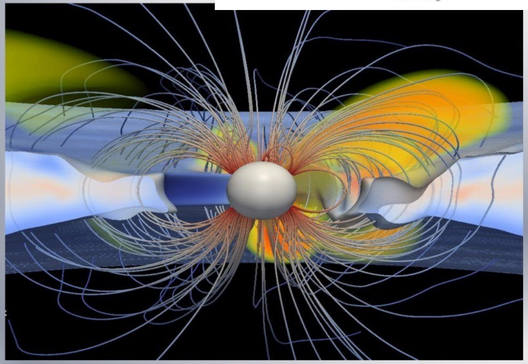




Turbulent r.m.s. velocity field in a 3D magnetized accretion disk. Flock et al., ApJ (2011) 735



Magnetic field strength in a 2D axisymmetric relativistic magnetized jet at the resolution of 40 zones per jet radius (R=1). The figure compares the results obtained with the HLLD solver (upper half) with the HLL solver (lower half), see Mignone et al, MNRAS (2009) 393, 1141.



MHD modeling of flares occurring in young stellar objects (YSOs) with the aim to investigate the effects of the flares on the stability of the circumstellar disk surrounding the central protostar, Orlando et al., MNRAS (2011) 415, 3380.

Pluto Code: A high-resolution shock-capturing (HRSC) code

- PLUTO is a **finite-volume, shock-capturing** code designed to integrate a system of conservation laws

$$\frac{\partial U}{\partial t} + \nabla . T = S(U)$$

- The code is particularly suitable for time-dependent, explicit computations of **highly supersonic flows in the presence of strong discontinuities**, and it can be employed under different regimes, i.e., classical, relativistic unmagnetized, and magnetized flows.

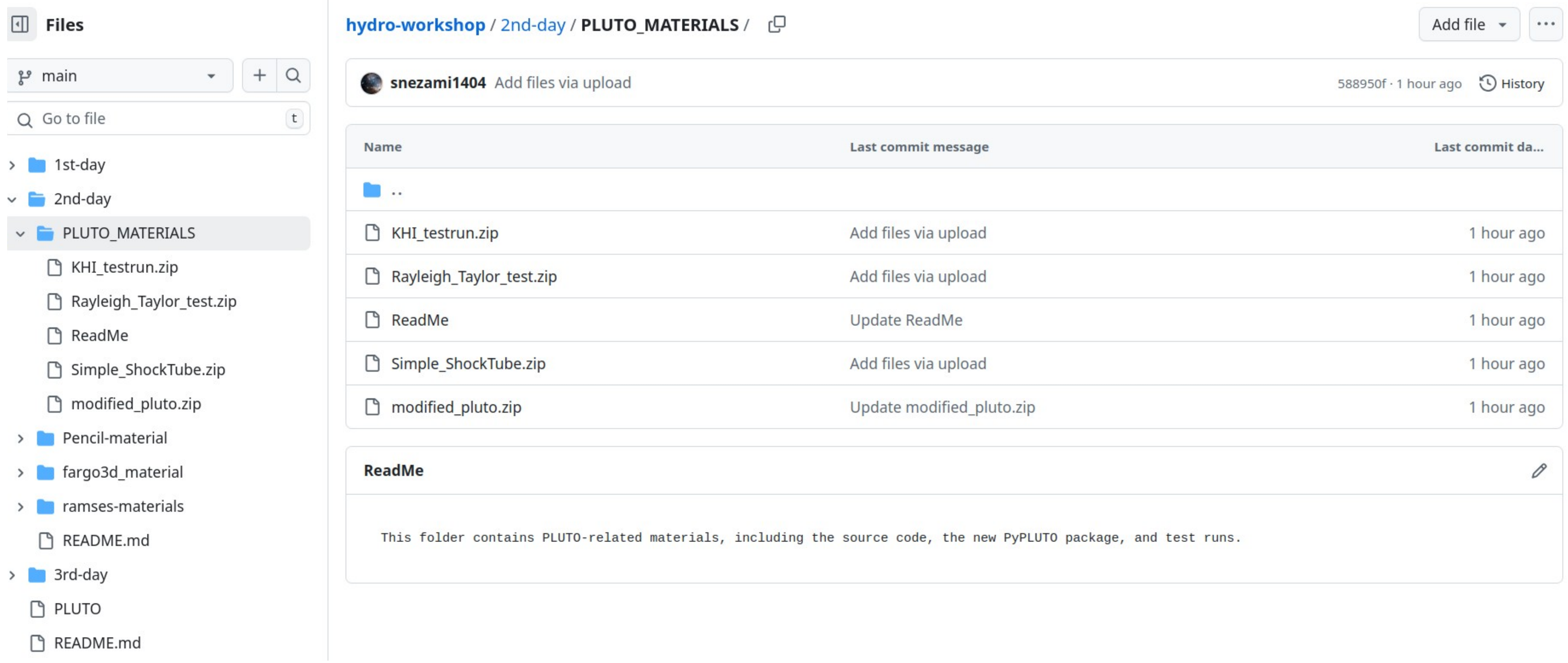
- PLUTO is written in C (~80,000 lines) and C++ (12,000 lines);

- Support multi-dimensional parallel (MPI) computations from single processor to a large number of cores (tested up to 262,144);

Downloading and unpacking PLUTO

- PLUTO can be downloaded from the following link **https://plutocode.ph.unito.it/**
- Once downloaded, extract all the files from the archive (pluto-4.4-patch3.tar.gz)

- Or you can download the file from the following repository:



Downloading and unpacking PLUTO

- PLUTO can be downloaded from the following link **https://plutocode.ph.unito.it/**
- Once downloaded, extract all the files from the archive (pluto-4.4-patch3.tar.gz):

```
~> gunzip        pluto-4.4-patch3.tar.gz
~> tar  -xvf     pluto-4.4-patch3.tar.gz
```

This will create the folder PLUTO/ in your home directory.

- To get the address of your PLUTO code

Change the directory to PLUTO

~> cd pluto-4.4-patch3/PLUTO

~/pluto-4.4-patch3/PLUTO> **pwd**

- At this point, we advise to set the environment variable PLUTO_DIR to point to your code directory.

Depending on your shell (e.g. tcsh or bash) use either one of the following commands

```
~> export   PLUTO_DIR=”/home/user/PLUTO “          # If you’re using the bash shell;
~> setenv  PLUTO_DIR =”/home/user/PLUTO “          # If you’re using the tcsh shell;
```

Or you can add the command in your bashrc to be known everywhere:

~> gedit .bashrc

- change the directory to $PLUTO_DIR and list the content

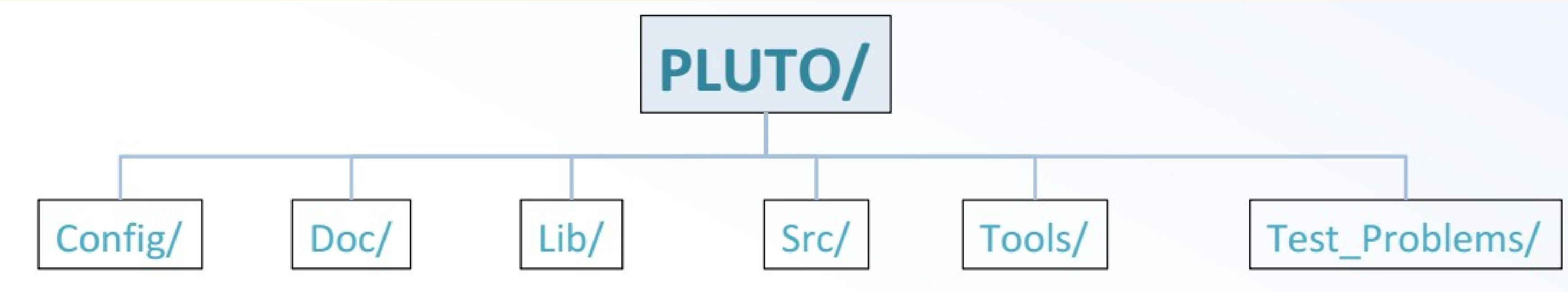
cd $PLUTO_DIR

~/pluto-4.4-patch3/PLUTO$ **ls -l**

- It should look like

```
Total 80

-rwxrwxrwx  1 nezami nezami 22404 Sep 18  2024 CHANGES
drwxrwxr-x  2 nezami nezami  4096 Nov  5 17:29 Config
-rw-r--r--  1 nezami nezami 17982 Apr 18  2011 COPYING
drwxrwxr-x  3 nezami nezami  4096 Feb 25 18:46 Doc
drwxrwxr-x  2 nezami nezami  4096 Nov  5 17:29 Lib
-rw-r--r--  1 nezami nezami  2091 Aug 22  2024 README
-rwxr-xr-x  1 nezami nezami  5304 Jul  7  2021 setup.py
drwxrwxr-x 21 nezami nezami  4096 Nov  5 17:29 Src
drwxrwxr-x  9 nezami nezami  4096 Nov  5 17:29 Test_Problems
drwxrwxr-x  7 nezami nezami  4096 Nov  5 17:29 Tools
```



In order to configure and setup PLUTO for a particular problem, four main steps have to be followed; the resulting configuration will then be stored in 4 different files, part of your local working directory:

definitions.h: header file containing all problem-dependent preprocessor directives required at compilation time (physics module, geometry, dimensions, etc.).

makefile: needed to compile PLUTO and it depends on your system architecture.

pluto.ini: startup initialization file containing run-time parameters (grid size, CFL,…)

init.c: implements initial, boundary conditions, etc.…

Lib/: repository for additional libraries;

Src/:main repository for all *.c source files with the exception of the init.c file,

Running a simple shock-tube problem

- Change directory to the test problem (sod)

Cd   …./shock_tube

- Run the Python script using
- ~…./sod> python $PLUTO_DIR/setup.py

- Then you need to compile the code for the current configuration and setup you chose
- ~…./sod> make

- You can now run the code by typing
- ~…./sod> ./pluto &
- or

> mpirun -np 4 ./pluto &

To Install mpi library

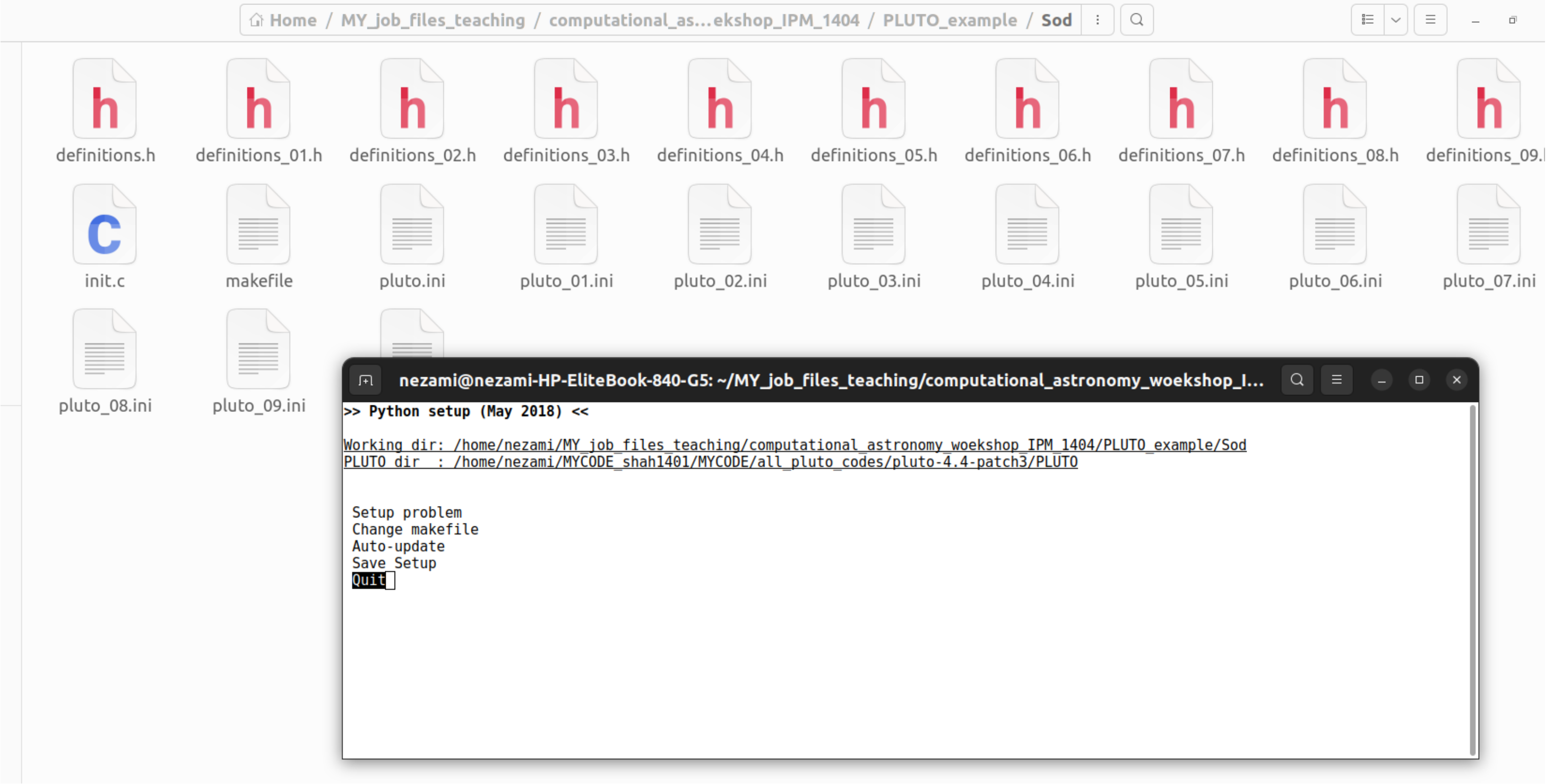
sudo apt update
sudo apt-get install libcr-dev mpich2 mpich2-doc

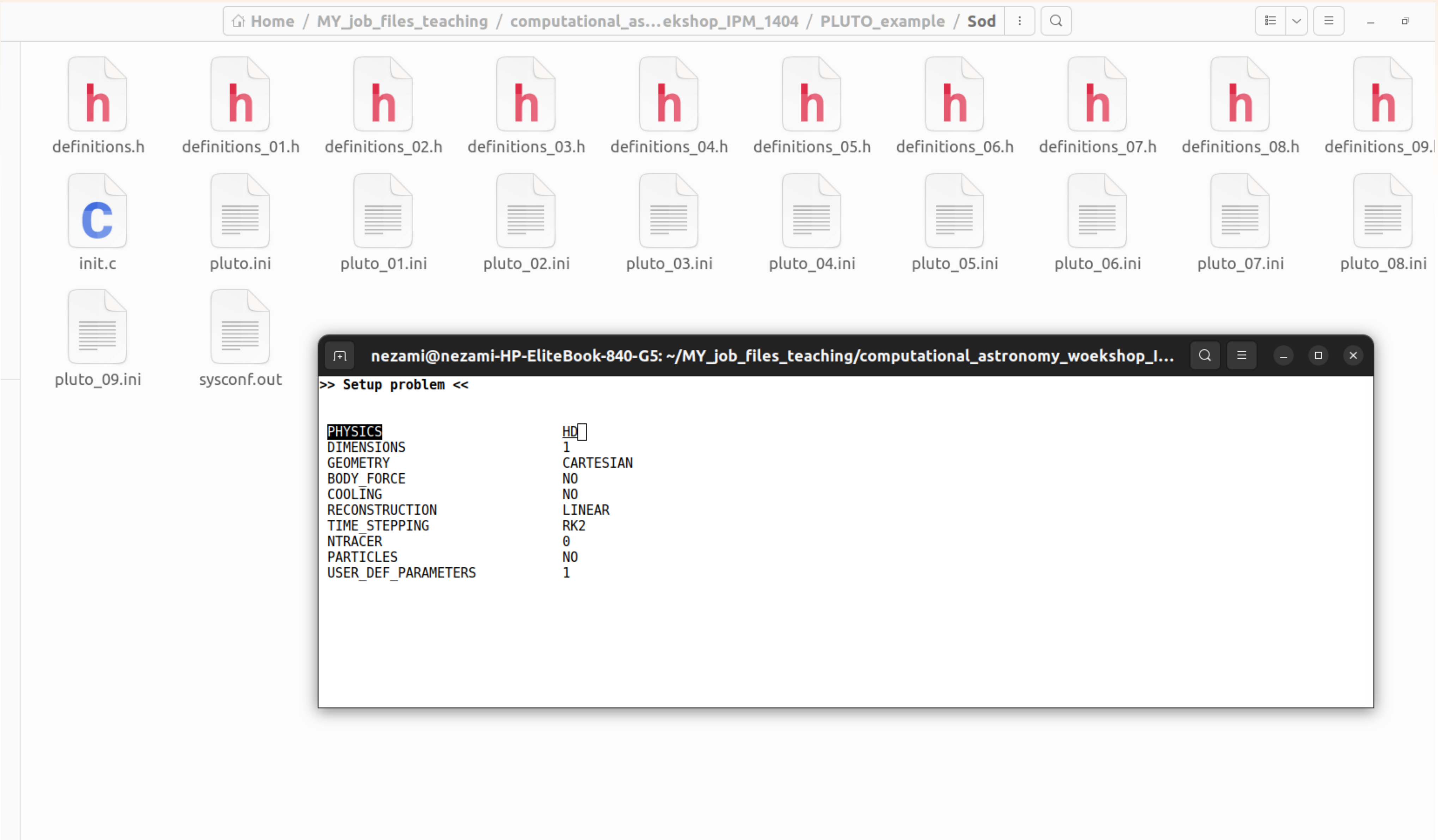
Running a simple shock-tube problem

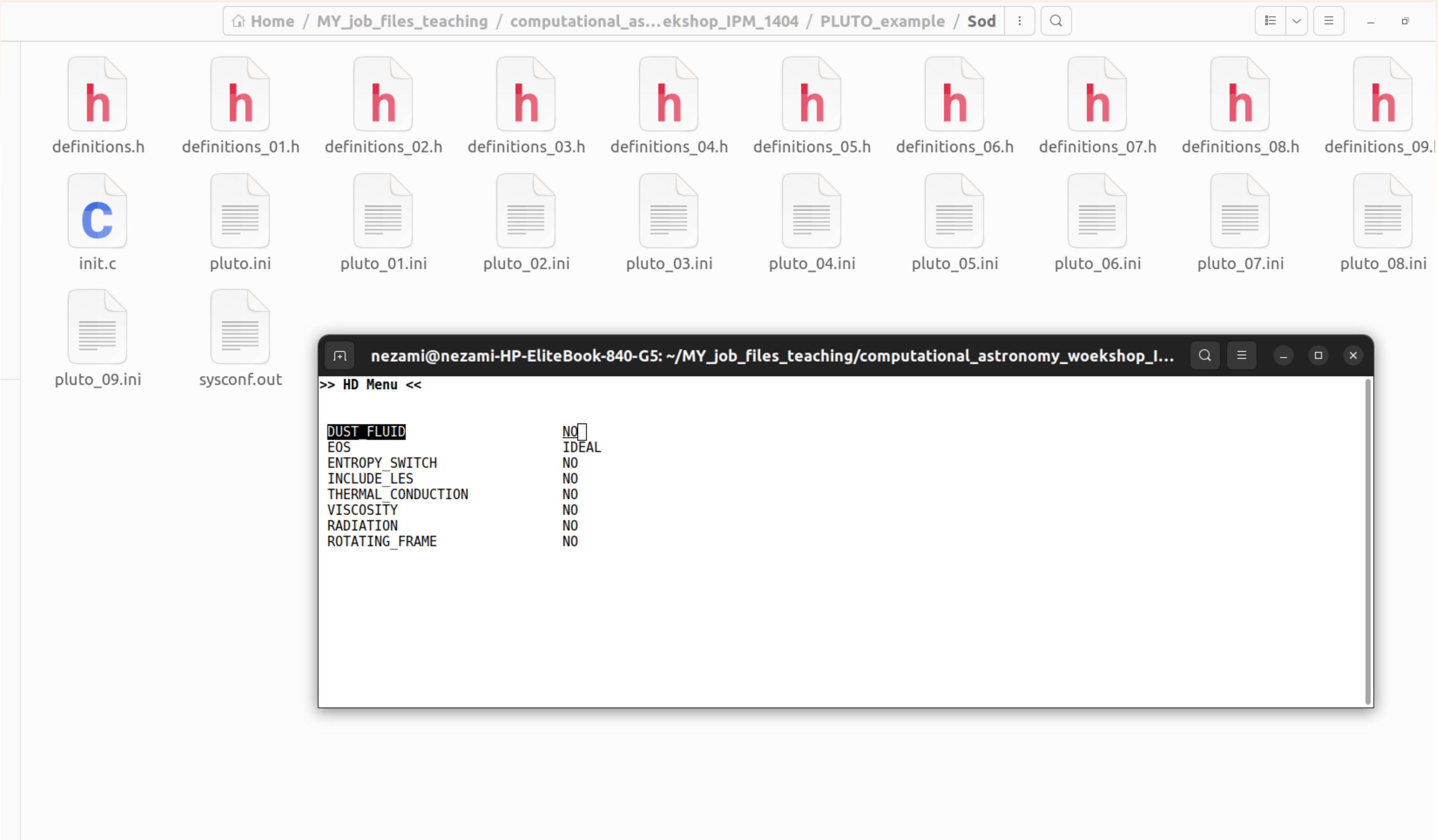
- Change directory to the test problem (sod)

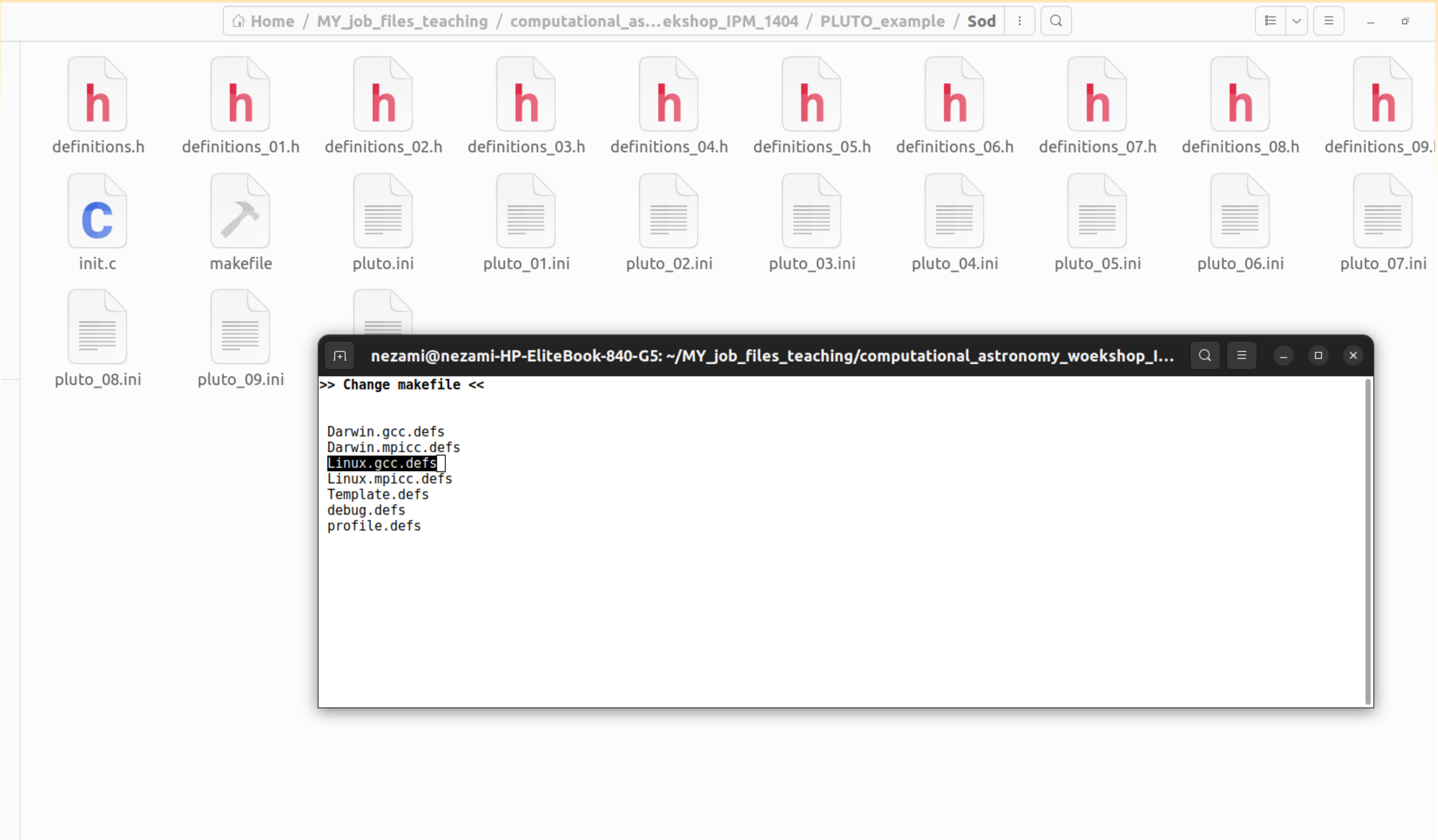
Cd   …./sod

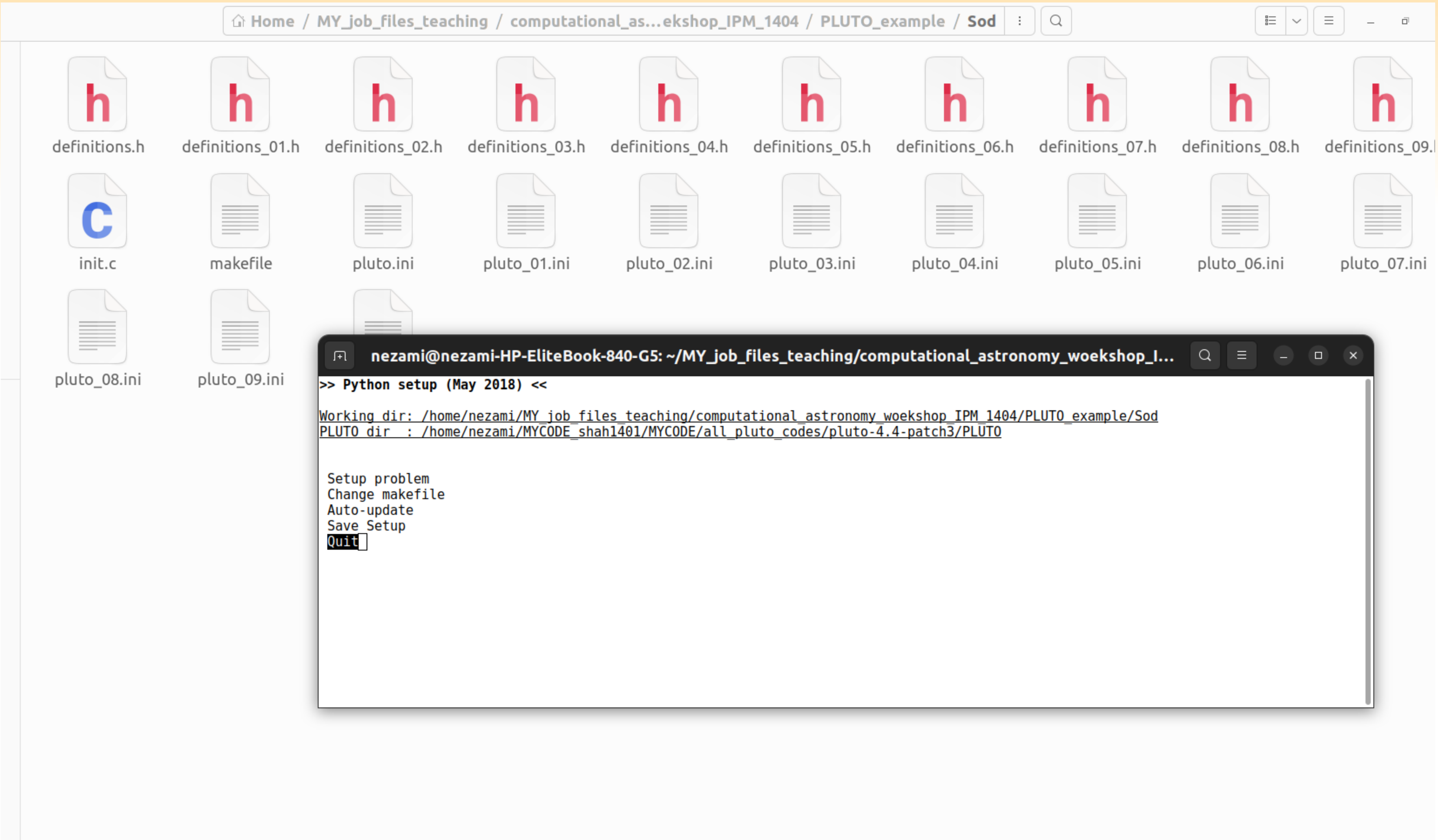
- Run the Python script using
- ~…./sod> python $PLUTO_DIR/setup.py
-




Home / MY_job_files_teaching / computational_as...ekshop_IPM_1404 / PLUTO_example / Sod
definitions.h
definitions_01.h
definitions_02.h
definitions_03.h
definitions_04.h
definitions_05.h
definitions_06.h
definitions_07.h
definitions_08.h
definitions_09.
init.c
pluto.ini
pluto_01.ini
pluto_02.ini
pluto_03.ini
pluto_04.ini
pluto_05.ini
pluto_06.ini
pluto_07.ini
pluto_08.ini
pluto_09.ini
sysconf.out
nezami@nezami-HP-EliteBook-840-G5: ~/MY_job_files_teaching/computational_astronomy_woekshop_I...
>> Setup problem <<
PHYSICS HD
DIMENSIONS 1
GEOMETRY CARTESIAN
BODY_FORCE NO
COOLING NO
RECONSTRUCTION LINEAR
TIME_STEPPING RK2
NTRACER 0
PARTICLES NO
USER_DEF_PARAMETERS 1


Home / MY_job_files_teaching / computational_as...ekshop_IPM_1404 / PLUTO_example / Sod
definitions.h
definitions_01.h
definitions_02.h
definitions_03.h
definitions_04.h
definitions_05.h
definitions_06.h
definitions_07.h
definitions_08.h
definitions_09.
init.c
pluto.ini
pluto_01.ini
pluto_02.ini
pluto_03.ini
pluto_04.ini
pluto_05.ini
pluto_06.ini
pluto_07.ini
pluto_08.ini
pluto_09.ini
sysconf.out
nezami@nezami-HP-EliteBook-840-G5: ~/MY_job_files_teaching/computational_astronomy_woekshop_I...
>> HD Menu <<
DUST_FLUID NO
EOS IDEAL
ENTROPY_SWITCH NO
INCLUDE_LES NO
THERMAL_CONDUCTION NO
VISCOSITY NO
RADIATION NO
ROTATING_FRAME NO


Home / MY_job_files_teaching / computational_as...ekshop_IPM_1404 / PLUTO_example / Sod
definitions.h
definitions_01.h
definitions_02.h
definitions_03.h
definitions_04.h
definitions_05.h
definitions_06.h
definitions_07.h
definitions_08.h
definitions_09.
init.c
makefile
pluto.ini
pluto_01.ini
pluto_02.ini
pluto_03.ini
pluto_04.ini
pluto_05.ini
pluto_06.ini
pluto_07.ini
pluto_08.ini
pluto_09.ini
nezami@nezami-HP-EliteBook-840-G5: ~/MY_job_files_teaching/computational_astronomy_woekshop_I...
>> Change makefile <<
Darwin.gcc.defs
Darwin.mpicc.defs
Linux.gcc.defs
Linux.mpicc.defs
Template.defs
debug.defs
profile.defs


Home / MY_job_files_teaching / computational_as...ekshop_IPM_1404 / PLUTO_example / Sod
definitions.h
definitions_01.h
definitions_02.h
definitions_03.h
definitions_04.h
definitions_05.h
definitions_06.h
definitions_07.h
definitions_08.h
definitions_09.
init.c
makefile
pluto.ini
pluto_01.ini
pluto_02.ini
pluto_03.ini
pluto_04.ini
pluto_05.ini
pluto_06.ini
pluto_07.ini
pluto_08.ini
pluto_09.ini
nezami@nezami-HP-EliteBook-840-G5: ~/MY_job_files_teaching/computational_astronomy_woekshop_I...
>> Python setup (May 2018) <<
Working dir: /home/nezami/MY_job_files_teaching/computational_astronomy_woekshop_IPM_1404/PLUTO_example/Sod
PLUTO dir : /home/nezami/MYCODE_shah1401/MYCODE/all_pluto_codes/pluto-4.4-patch3/PLUTO
Setup problem
Change makefile
Auto-update
Save Setup
Quit

pluto.ini

~/MY_job_files_teaching/computational_astrono...404/PLUTO_example/Shock_tube/Simple_ShockTube

```
[Grid]

X1-grid   1   0.0   400   u   1.0
X2-grid   1   0.0     1   u   1.0
X3-grid   1   0.0     1   u   1.0

[Chombo Refinement]

Levels           4
Ref_ratio        2 2 2 2 2
Regrid_interval  2 2 2 2
Refine_thresh    0.3
Tag_buffer_size  3
Block_factor     4
Max_grid_size    32
Fill_ratio       0.75

[Time]

CFL            0.8
CFL_max_var    1.1
tstop          1
first_dt       1.e-4

[Solver]

Solver         roe

[Boundary]

X1-beg      outflow
X1-end      outflow
X2-beg      periodic
X2-end      periodic
X3-beg      outflow
X3-end      outflow

[Static Grid Output]

uservar    0
dbl        0.2  -1   single_file
flt       -1.0  -1   single_file
vtk       -1.0  -1   single_file
tab       -1.0  -1
```

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Open Save

definitions.h

~/MY_job_files_teaching/computational_astro...4/PLUTO_example/Shock_tube/Simple_ShockTube

```c
#define  PHYSICS                        HD
#define  DIMENSIONS                     1
#define  GEOMETRY                       CARTESIAN
#define  BODY_FORCE                     NO
#define  COOLING                        NO
#define  RECONSTRUCTION                 LINEAR
#define  TIME_STEPPING                  RK2
#define  NTRACER                        0
#define  PARTICLES                      NO
#define  USER_DEF_PARAMETERS            1

/* -- physics dependent declarations -- */

#define  DUST_FLUID                     NO
#define  EOS                            IDEAL
#define  ENTROPY_SWITCH                 NO
#define  INCLUDE_LES                    NO
#define  THERMAL_CONDUCTION             NO
#define  VISCOSITY                      NO
#define  RADIATION                      NO
#define  ROTATING_FRAME                 NO

/* -- user-defined parameters (labels) -- */

#define  SCRH                           0

/* [Beg] user-defined constants (do not change this line) */

#define  INTERNAL_BOUNDARY              NO
#define  LIMITER                        MINMOD_LIM
#define  CHECK_DIVB_CONDITION           NO
#define  ASSIGN_VECTOR_POTENTIAL        NO
#define  UPDATE_VECTOR_POTENTIAL        NO
#define  WARNING_MESSAGES               NO
#define  PRINT_TO_FILE                  YES
#define  MULTIPLE_LOG_FILES             NO

/* [End] user-defined constants (do not change this line) */
```

Loading file "/home/nezami/MY_job_files_teaching/computational_astronomy_woekshop_IPM_1404/PLUTO_example/Shock_tube/Simple_ShockTub... C/ObjC Header Tab Width: 8 Ln 1, Col 1 INS

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Open

*init.c
~/MYCODE_shah1401/MYCODE/all_pluto_codes/pluto-4.4-patch3/PLUTO/Src/Templates

Save

```c

/* ///////////////////////////////////////////////////////////////////// */
/*!
  \file
  \brief Contains basic functions for problem initialization.

  The init.c file collects most of the user-supplied functions useful
  for problem configuration.
  It is automatically searched for by the makefile.

  \author A. Mignone (andrea.mignone@unito.it)
  \date   March 5, 2017
*/
/* ///////////////////////////////////////////////////////////////////// */
#include "pluto.h"

/* ********************************************************************* */
void Init (double *v, double x1, double x2, double x3)
/*!
 * The Init() function can be used to assign initial conditions as
 * as a function of spatial position.
 *
 * \param [out] v   a pointer to a vector of primitive variables
 * \param [in] x1   coordinate point in the 1st dimension
 * \param [in] x2   coordinate point in the 2nd dimension
 * \param [in] x3   coordinate point in the 3rdt dimension
 *
 * The meaning of x1, x2 and x3 depends on the geometry:
 * \f[ \begin{array}{cccl}
 *    x_1  & x_2    & x_3  & \mathrm{Geometry}    \\ \noalign{\medskip}
 *     \hline
 *    x    &   y    &  z   & \mathrm{Cartesian}   \\ \noalign{\medskip}
 *    R    &   z    &  -   & \mathrm{cylindrical} \\ \noalign{\medskip}
 *    R    & \phi   &  z   & \mathrm{polar}       \\ \noalign{\medskip}
 *    r    & \theta & \phi & \mathrm{spherical}
 *    \end{array}
 *  \f]
 *
 * Variable names are accessed by means of an index v[nv], where
 * nv = RHO is density, nv = PRS is pressure, nv = (VX1, VX2, VX3) are
 * the three components of velocity, and so forth.
 *
 *********************************************************************** */
{
```

C   Tab Width: 8   Ln 2, Col 1   INS

Visualization with PyPLUTO

• To install PyPLUTO (Python ≥3.10 required):

```
> cd $PLUTO_DIR/Tools/PyPLUTO/Src
> pip install -e ./
```

• This should install all the necessary packages (numpy, matplotlib, scipy, pandas).

• The -e command will prevent from installing the package every time is updated (simply replacing the files will be sufficient)

• If issues arise, try:

```
> cd $PLUTO_DIR/Tools/PyPLUTO/Src
> python setup.py install
```

• For LINUX UBUNTU 24.04 LTS system

You can try:

```
>pip install -e ./ --break-system-packages
```

Visualization with PyPLUTO

- All output files can be loaded with PyPLUTO:

```
import pyPLUTO as pp
D = pp.Load(0)
I = pp.Image().plot(D.x1,D.rho)
pp.show(block = False)
```

- This will produce a 1D plot (x,y) of the initial condition ('0000').

```
import pyPLUTO as pp
D = pp.Load()
I = pp.Image()
I.plot(D.x1, D.rho, label = 'rho', legpos = 0)
I.plot(D.x1, D.prs, xtitle = 'x')
pp.show()
```

RAYLEIGH-TAYLOR INSTABILITY

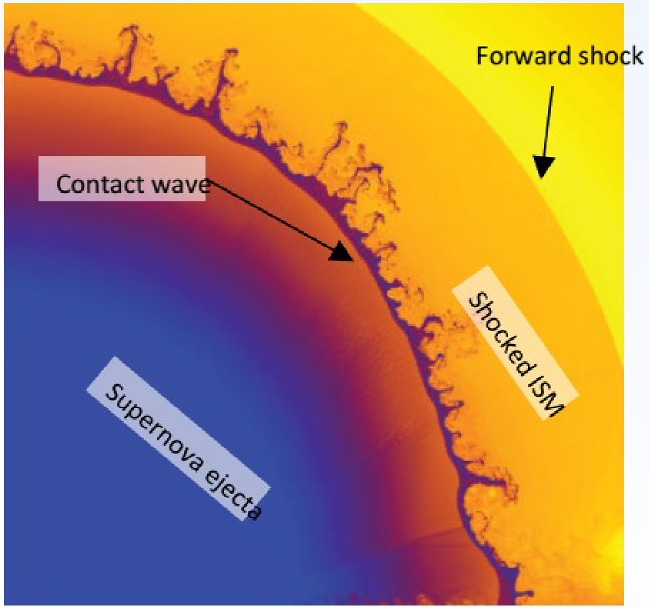
- The Rayleigh–Taylor instability (RTI) is a classical fluid instability that occurs at the interface between two fluids of different densities when the lighter fluid pushes against the heavier one under the influence of gravity.

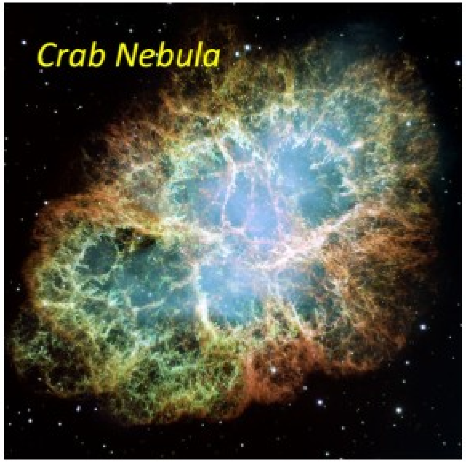
- The amplitude growths and the further upward motion of the lighter fluid assumes the form of rising bubble while the sinking fluid become finger-shaped

- As the instability proceeds, fingers evolve into mushroom-like vortex motion accompanied by secondary shear flow instabilities.

- n a supernova (SN) explosion a large amount of energy is released resulting in a formation of a large scale SN remnant (SNR)

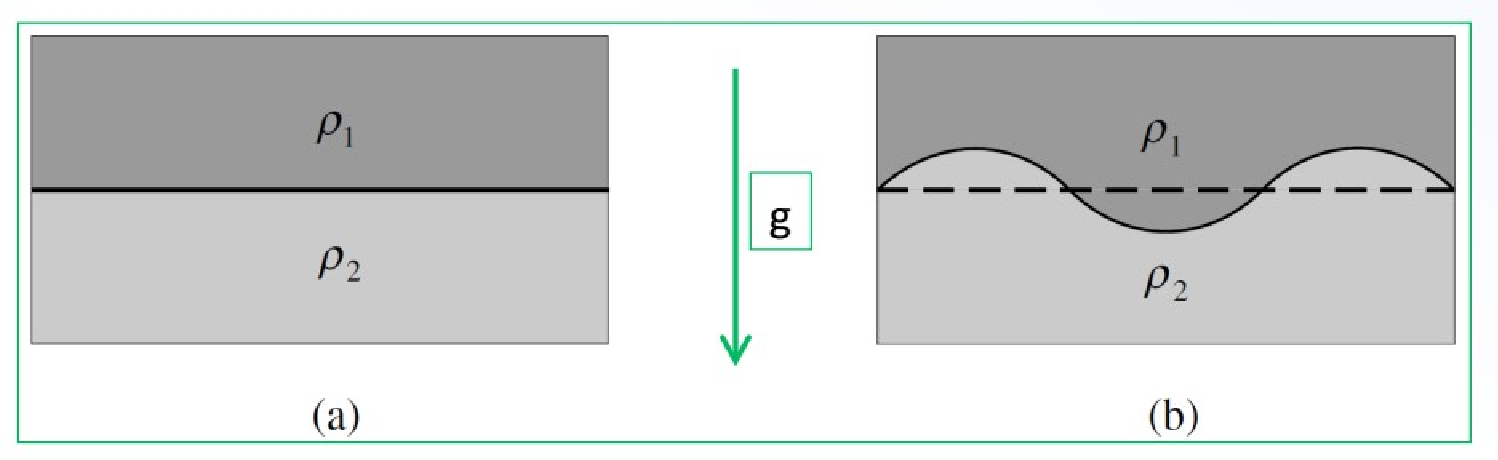
- The dense shell of ejected material decelerates in a rarefied interstellar medium (ISM) and is unstable to RT-type instabilities.





RAYLEIGH-TAYLOR INSTABILITY (RTI:Analysis)

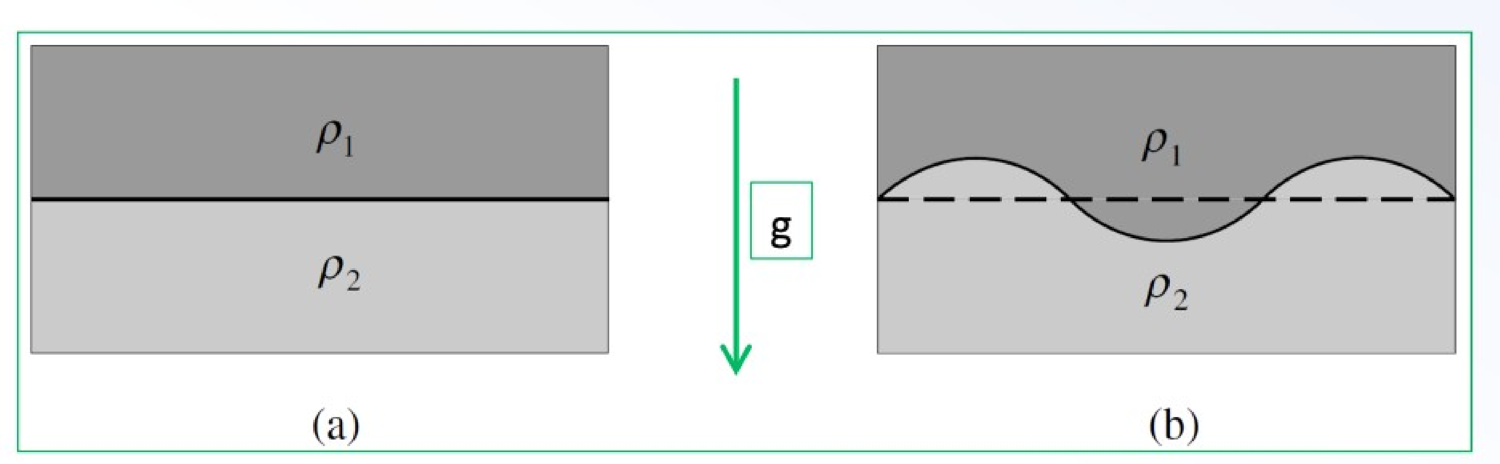
Consider the case where two fluids with densities ρ1 and ρ2 are on top of each other .



This is an equilibrium situation if the stratification is supported by a pressure gradient:

$$\nabla P = \rho g$$

RAYLEIGH-TAYLOR INSTABILITY (RTI:Analysis)

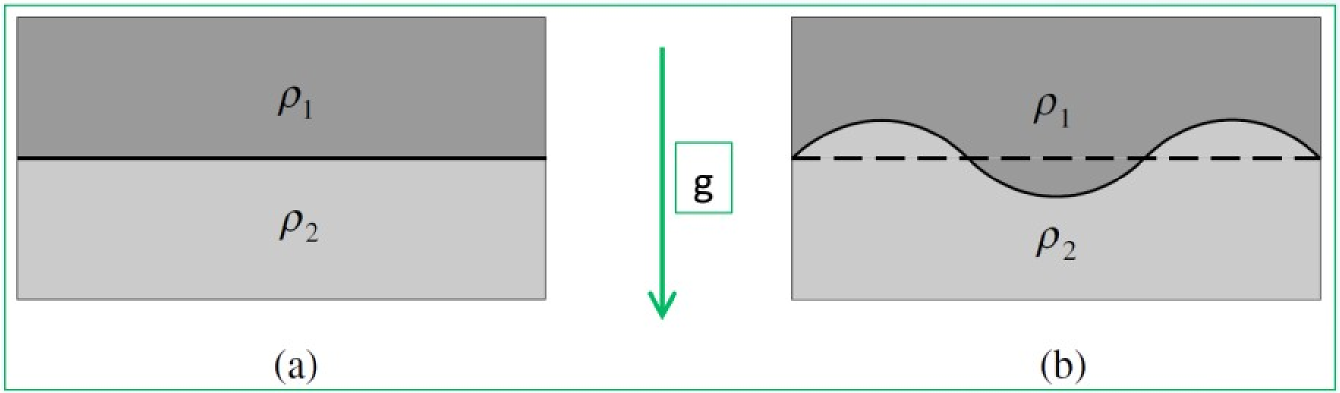


Let’s now perturb the equilibrium by rippling the boundary layer.

- The fluid element of density ρ1 has moved downwards with consequent loss of gravitational potential energy while the opposite is true of the fluid element of density ρ2.

- It is intuitively obvious that the only stable equilibrium is to have the denser fluid supporting the less dense. The instability that arises when ρ2 < ρ1 is called the Rayleigh–Taylor instability.

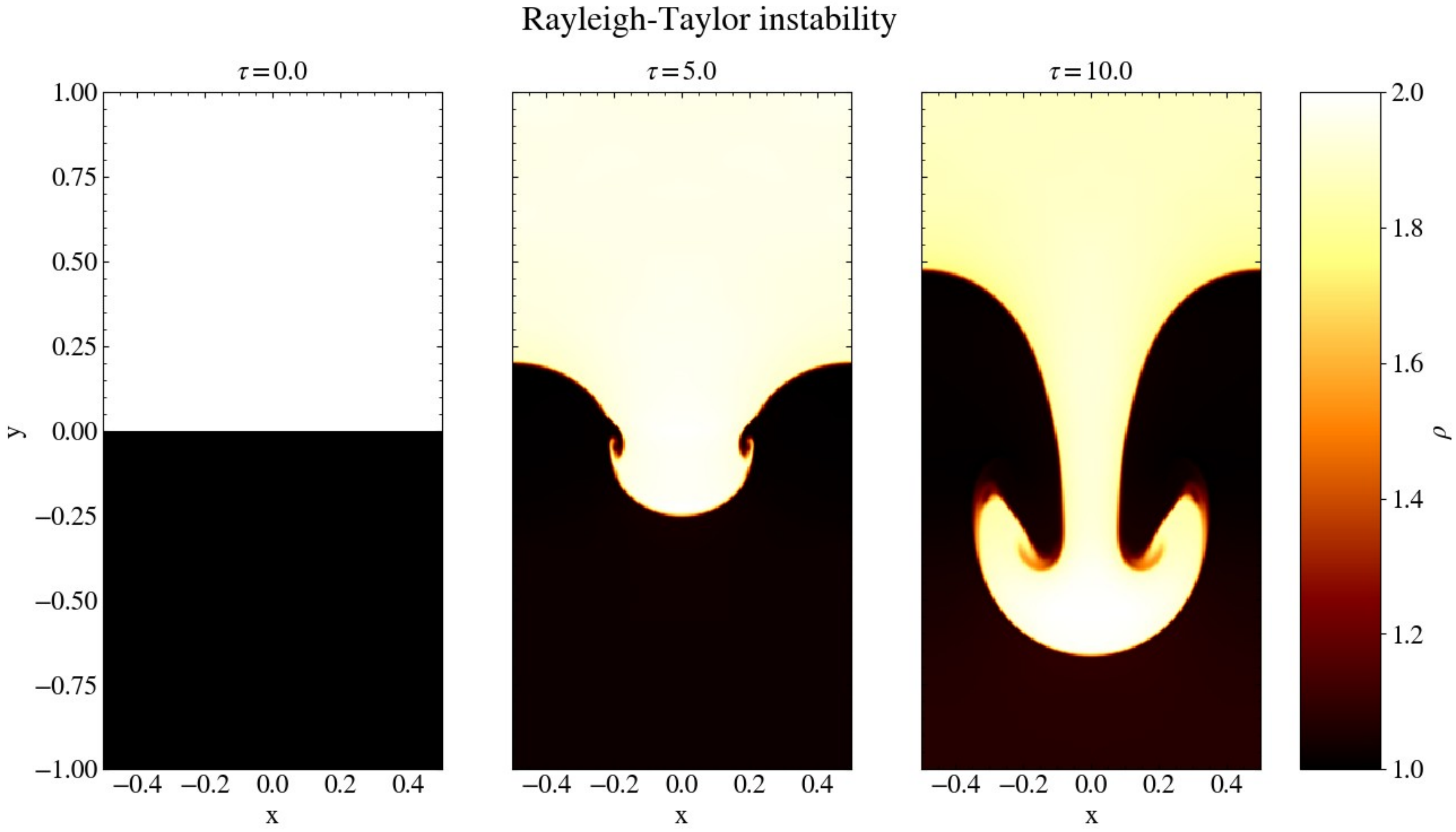
RTI: Linear Analysis



From normal mode analysis it is found that, in absence of magnetic field,

$$\boxed{\omega^2 = -\frac{kg(\rho_1 - \rho_2)}{\rho_1 + \rho_2}}$$

- If ρ1 < ρ2 the equilibrium is stable ➡ a surface gravity waves
- If ρ1>ρ2 the equilibrium is unstable ➡ a Rayleigh-Taylor instability


Rayleigh-Taylor instability
τ = 0.0
τ = 5.0
τ = 10.0
y
x
ρ
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
−0.4
−0.2
0.0
0.2
0.4
2.0
1.8
1.6
1.4
1.2
1.0