Exploring A New Astrophysical Gas Dynamical Instability on GPUs

Ian Ruh, Tim Waters

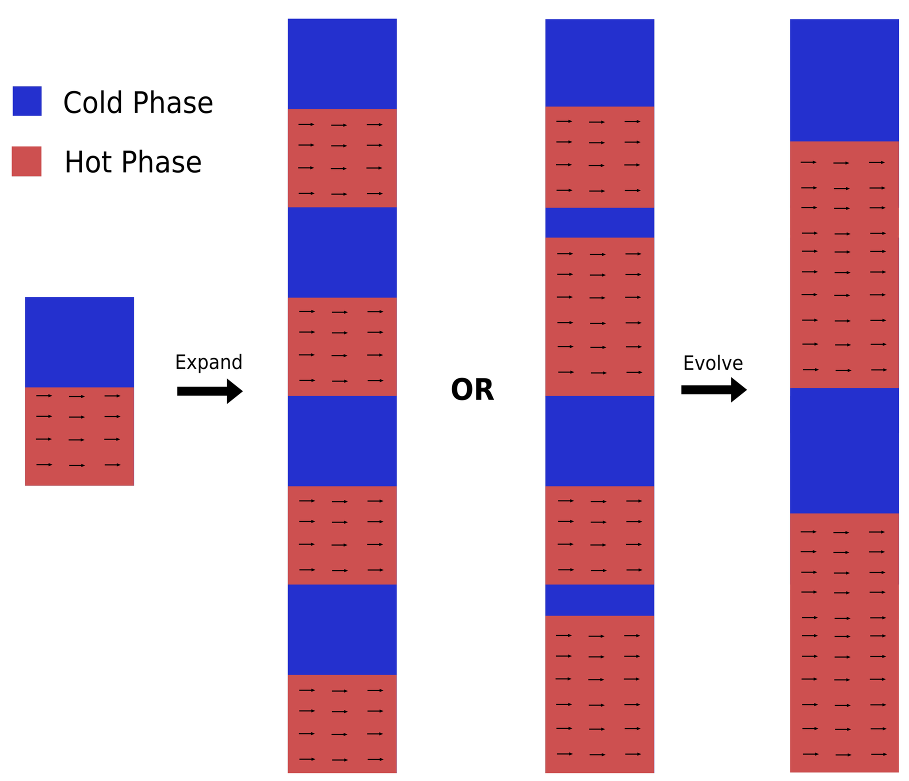
2019 Student Symposium
August 7, 2019

Abstract

The Kelvin-Hemholtz instability (KHI) is a classic hydrodynamics problem that has been studied extensively. The instability arises when two smooth flows of different velocity interact at a perturbed boundary, ultimately resulting in turbulent flow. In our study we look at a modified setup of the Kelvin-Helmholtz instability where instead of just 1 set of shearing slabs with different densities, there are two sets. This setup serves as local model for astrophysical environments with adjacent filamentary structures, e.g. supernova remnants or ISM clouds. It was recently pointed out that in addition to KHI, there is an independent dynamical instability that will cause the denser slabs to coalesce [1]. In our study we examine the interaction of KHI and 'cloud coalescence'. In particular, we assess whether or not a time varying radiation flux can speed up the coalescence process, so that it occurs on dynamical time scales, thereby competing with KHI. In order to perform the study, we modified a public GPU accelerated hydrodynamics code (Cholla) [2] to include thermal conduction, allowing us to self-consistently model the interfaces between the hot and cold gas phases.

Introduction

The formation and evolution of multiphase gas structures has become the topic of some disagreement. It has been suggested that there is a tendency for gas clouds undergoing cooling to split up into "cloudlets" in order to retain a locally balanced pressure equilibrium [3]. Recently, however, it has been pointed out that there is another process operating that would cause cold-phase clouds to coalesce. In our study we look at how radiation fluxes impact the time scale upon which this new dynamical instability operates.



From left to right: Standard Kelvin-Helmholtz instability; Standard Kelvin-Helmholtz setup expanded with periodic boundary conditions; Our initial condition with asymmetric gas clouds; Our expected final state after the clouds coalesce.

GPU Utilization

A significant part of the study was spent modifying the GPU code Cholla [2] in order to incorporate thermal conduction. Part of the challenge with incorporating conduction was minimizing repetitive calculations while also trying to limit the number of off chip and uncached memory fetches (which can take orders of magnitude more clock cycles than on-chip memory).

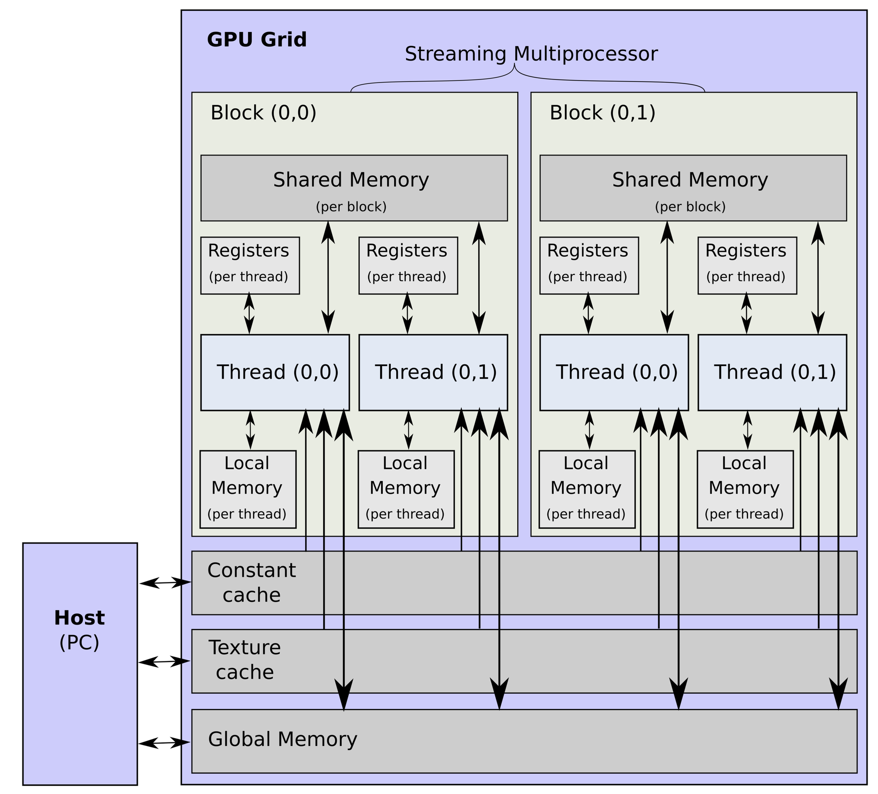
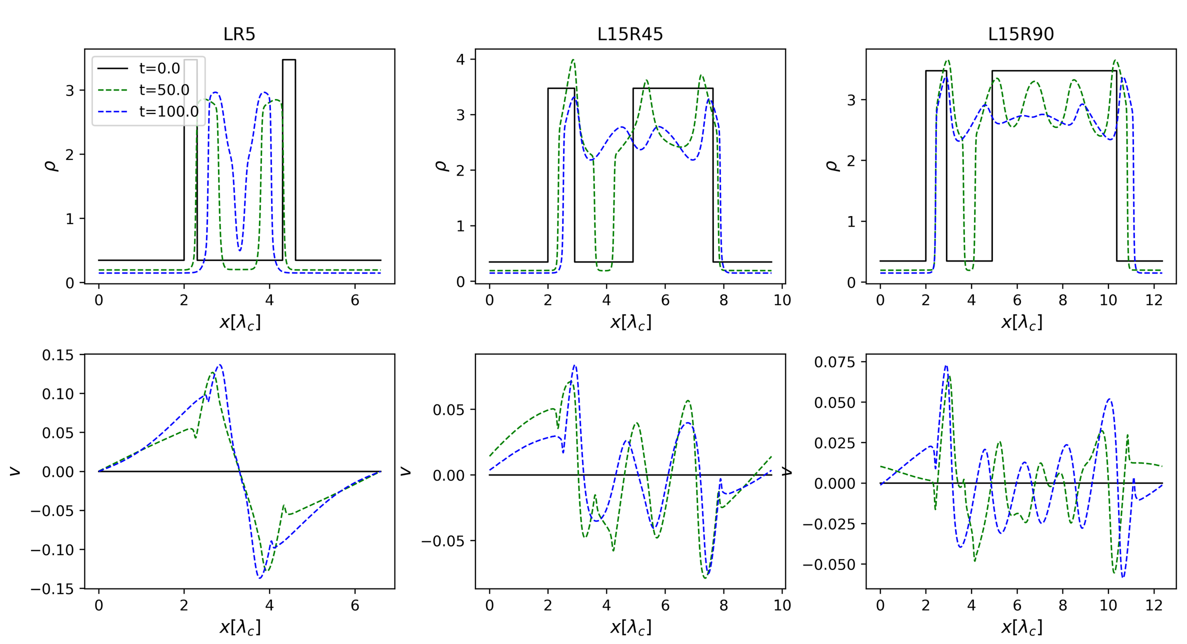


Diagram of an Nvidia GPU memory model. The global memory is by far the slowest to read from. The texture memory, constant cache, and local memory are subsets of global memory that are cached on chip, but backed by global memory. Shared memory is purely on-chip and resides in the L1 and L2 caches. Register memory is the fastest, but cannot be directly controlled.

Method

We focused on three primary parameters throughout the study, namely the period and magnitude of the radiative heating, and the size of the clouds.



Three of our 1D runs for different initial clouds sizes (LR5, L15R45, L15R90). Observing the $t = 50.0$ plot across the three setups, it's clear that the time it takes for the clouds to coalesce decreases as the right cloud gets larger.

Results

As noted previously, our results are in agreement with Waters & Proga [4] that an increase in the ratio of clouds sizes decreases the time it takes for coalescence to occur as the pressure imbalances between the clouds gets larger. We also found that an increase in the magnitude of the radiative heating consistently decreased the coalescence time (as illustrated below). However, the relationship between the period of the heating and the coalescence time requires further study as it doesn't appear to consistently make it faster or slower.

Table: L15R90 Amplitude Variation

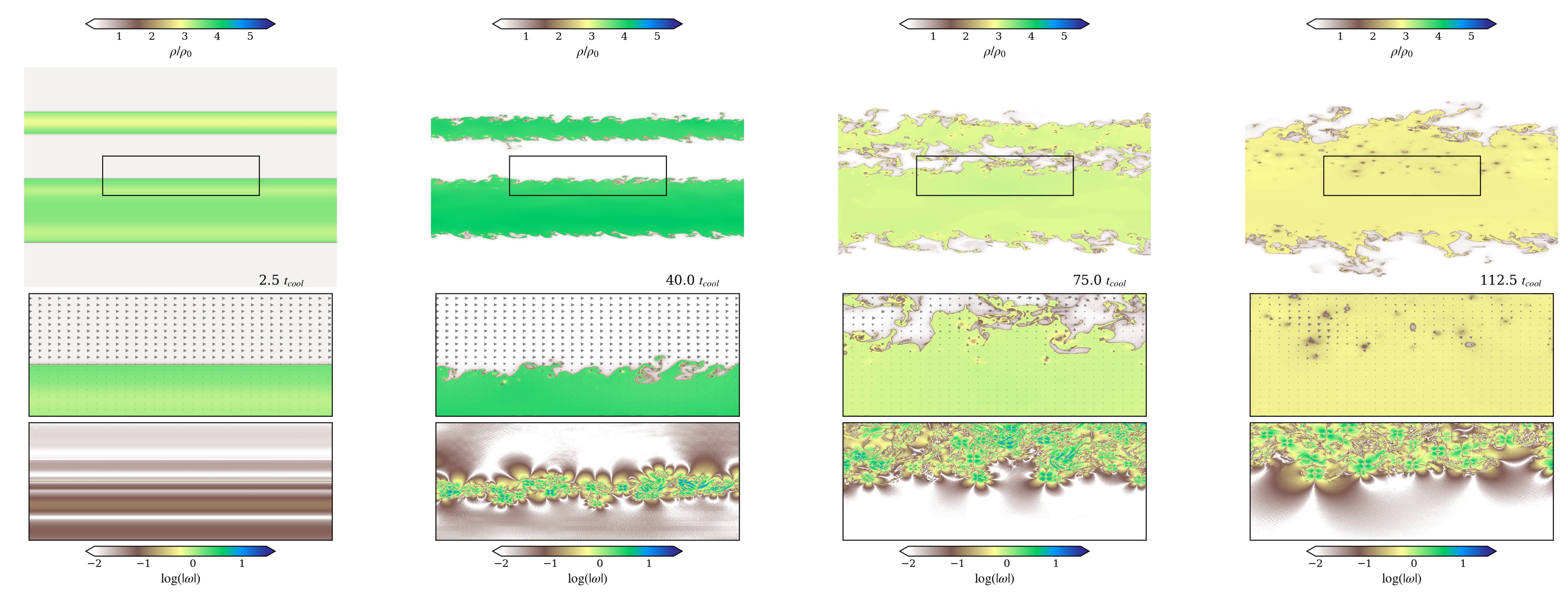
Amp	Period	Coalescence Time
0.00	N/A	67.5
0.05	1.0	67.2
0.10	1.0	66.8
0.15	1.0	66.2
0.20	1.0	65.5
0.25	1.0	64.0

Table: L15R90 Period Variation

Amp	Period	Coalescence Time
0.15	0.5	65.2
0.15	1.0	66.2
0.15	1.5	67.0
0.15	2.0	68.2
0.15	2.5	68.0
0.15	3.0	66.8
0.15	3.5	66.0
0.15	4.0	65.8
0.15	4.5	65.8
0.15	5.0	65.8
0.15	10.0	65.2
0.15	25.0	65.8

(1) (2) (3) (4)

Videos illustrating our results. (1) Shows the changes in behavior due to variations in the amplitude for a L15R45 cloud setup. (2) Illustrates changes in period for the LR5 cloud setup. (3) Video of 2D simulation run of L15R45 setup with hot phase velocity $0.1\lambda_c$ (see below for explanation). (4) Video of 2D simulation run with hot phase velocity $0.5\lambda_c$ (see below for explanation).



The figures above demonstrate the competition between KHI and the dynamical instability for the L15R45 . This simulation was conducted with an initial velocity of the hot gas at $0.1\lambda_c$. The turbulence that can be observed at $t = 40.0$ and $t = 75.0$ in the figures above grows as the hot gas's velocity increases to the point that it prevents the coalescence of the cold gas clouds. (See (3) & (4) QR codes above for full videos of both coalescing clouds and turbulent clouds)

References

1. Waters, T., & Proga, D. 2019, ApJ, 875, 158
2. Schneider & Robertson, 2015, ApJS
3. McCourt, M., Oh, S. P., OLeary, R., & Madigan, A.-M. 2018, MNRAS, 473, 5407
4. Waters, T., & Proga, D. 2019, ApJ, 876, L3