Computational Analysis of Mixing Layers in the Interstellar Medium

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Introduction

The Kelvin-Helmholtz Instability manifests when a perturbation, caused by motion of two fluids of distinct density relative to each other, proliferates via Bernoulli effect into wide-scale disruption in the fluids' initial motion. Our project's focus is centered on the relation of said instability to the mixing layer—the interface between "hot" (~10^6 K) and "warm" (~10^4 K) gases—in the gas clouds of the interstellar medium (ISM). More specifically, our project seeks to verify the reason for which the ISM is populated by less gas of intermediate, mixing-layer temperature than would be expected by simple averaging of the distinct gas types through computational methods. To achieve this, we simulated representative conditions in the ISM using Athena++. We then analyzed the results using Python.

Background

The interstellar medium consists of multitudinous gas clouds. Despite the assumption that, given the massive surface area of the interface due to the unstable mixing, the entirety of the gas will quickly reach an intermediate temperature at the geometric mean of the warm and hot temperatures, the two gases remain segregated. The degree to which they are separated is unexpected. To account for this, Begelman posits that a rapid radiative cooling function acting on the intermediate-temperature gas makes it less stable and causes it to quickly replenish the stock of "warm" gas. This explains the continued existence of the mixing layer—it doesn't proliferate quickly enough to overtake the entire ISM, as would initially have been predicted, and reaches a steady state. The necessary cooling function to maintain this steady state is provided in (Begelman et. al), which can be represented as $(5/2)\eta_h p v_t = (5/2) p f_i l / t_{cool}\langle T\rangle$—this shows the equivalence between the cooling rate of the mixing layer and the energy output of the contained hot gas. Further, this equation can also be represented as $l f_i \sim \eta_h v_t t_{cool}\langle T\rangle$. In both cases, η_h represents the fraction of mass and energy deposited in the mixing layer by incoming eddies,velocity v_t, pressure p, $t_{cool}\langle T\rangle$ "the cooling time-scale at temperature T," f_i the volume filling factor of the intermediate phase, and l the thickness.

Methods

Our simulation was written using Athena++, a magnetohydrodynamics (MHD) simulator created in C++ by (Stone et. al). To use the software, we defined initial conditions and key physical phenomena (physical source terms) within a meshgrid computational box and then allow Athena++ to numerically calculate the system's state periodically at later times. We ran 2 simulations with different sizes and lengths. A 25x10 parsec box for 50 million years, and a 20x10 parsec box for 20 million years. In order to simulate the interface between hot and warm gas, we placed two different states of gas in our simulation box, with an interface between them along the x-axis. The two gasses initially varied in mass density, temperature, and pressure. We also gave the hot gas momentum along the interface. We varied mass density and velocity using a hyperbolic tangent function close to the interface to avoid an unrealistic discontinuity. We then gave the hot gas momentum directed into the warm gas using to a set of 32 harmonics with random phases. This process simulates a random perturbation that creates the Kelvin-Helmholtz instability. We also simulated the radiative cooling of the gas using a function which calculates the expected change in temperature of a region of gas based on its current temperature. Finally, we used a periodic boundary on our box in the x direction to represent the ongoing nature of the interface. The positive y boundary is reflecting, preventing the warm gas from escaping and representing its essentially unlimited supply. The negative y boundary uses a ghost zone, which is a small continuation of the simulation off screen. This gas does not enter the simulation box, but allows us to represent the continuing supply of hot gas beyond. The left and right side boundary conditions are periodic.

Analysis

To analyze our data we looked at several different ways to show evidence of a stable mixing layer between the two distinct temperature regions. The average velocity in the y direction graph weighted by volume of each cell shows us that initially the instability takes off and increases the average velocity greatly, but as the simulation goes on we see the average velocity of the box begin to fluctuate around a steady velocity value of approximately 450 km/s. We can also examine the average temperature over time for the simulation and find a similar phenomenon occuring where we see the temperature fluctuating around approximately 2.5 x 10^5 K which is what all of our references on mixing layers expected to see. This shows a large amount of gas staying at a steady temperature which happens to be the intermediate temperature between the two distinct regions. We also made PDFs for both temperature (volume weighted) and density (both volume and mass weighted) of the gases. We have videos of these along with other movies of the project in our presentation slides. The PDFs show a large region in the intermediate values between the two distinct regions and our plot of the cooling time also suggests the fastest cooling time in the entire plot is occurring in the interface between the two gases. This tells us that the cooling function is in fact peaking for the intermediate temperature gas, which is exactly what is desired for the stable mixing layer to occur for long periods of time.

Results

Our simulations show distinct evidence of the "stable" mixing layer. Looking at Figure 3 and Figure 4 we are able to see that there is a semi steady state that the gases come to. This is evidence that the cooling function is counteracting the effects of the Kelvin-Helmholtz instability occurring between the hot and warm regions of gas. We clearly see the average temperature fluctuating around the expected 1e5 Kelvin.

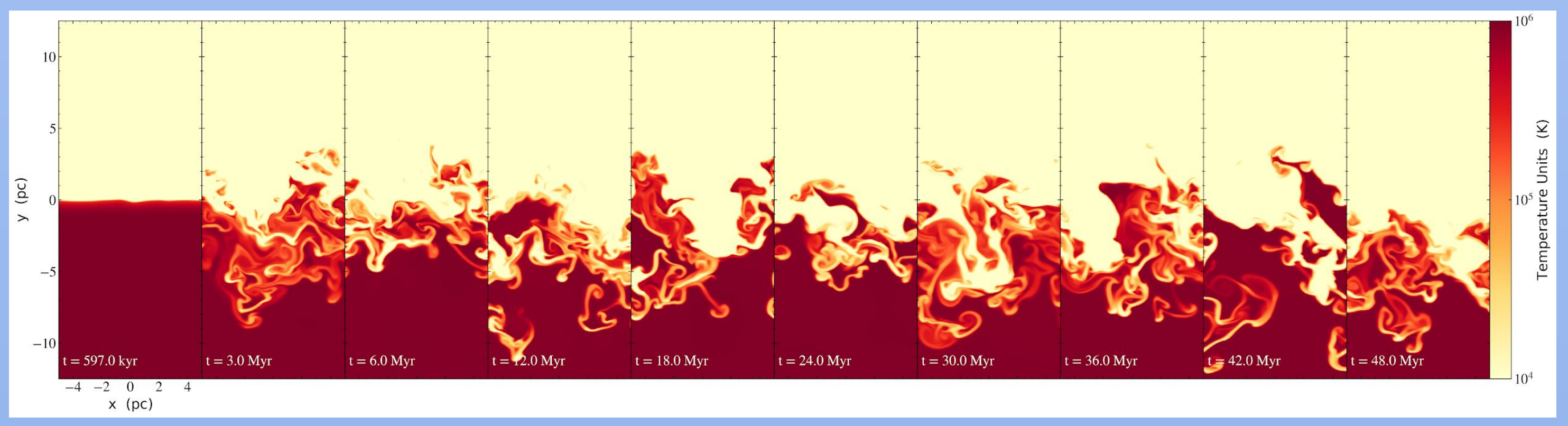

Figure 1: In this figure we see the time evolution of the simulation by looking at time slices throughout it. The plot is of temperature. This simulation ran for a simulated time of 50 Myr and the computational box has dimensions of 25 pc x 10 pc. In this simulation the hyperbolic tangent profile used for the initial conditions has its transition mainly in the center of the computational box.

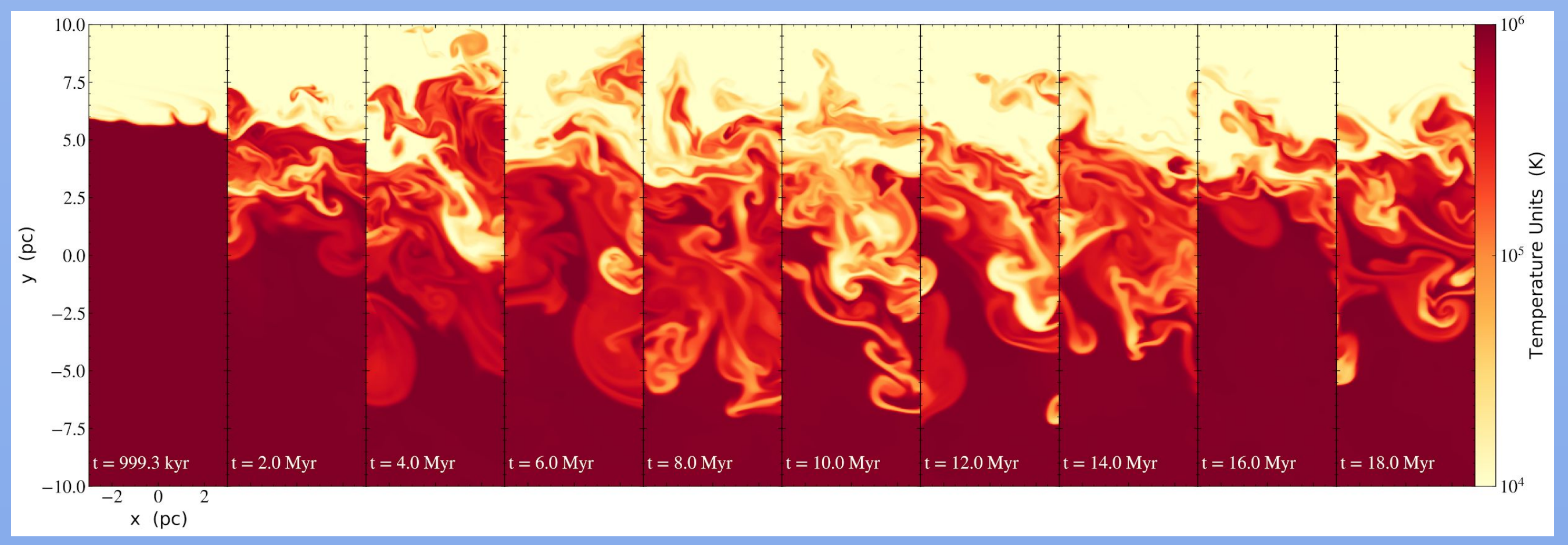

Figure 2: This figure is a slightly modified simulation. The only differences is that the computational box has dimensions 20 pc x 10 pc, the simulation ran for a simulated time of 20 Myr, and the hyperbolic tangent profile was shifted upwards to prevent the cold gas from possibly affecting the user boundary conditions created at the bottom of the box.

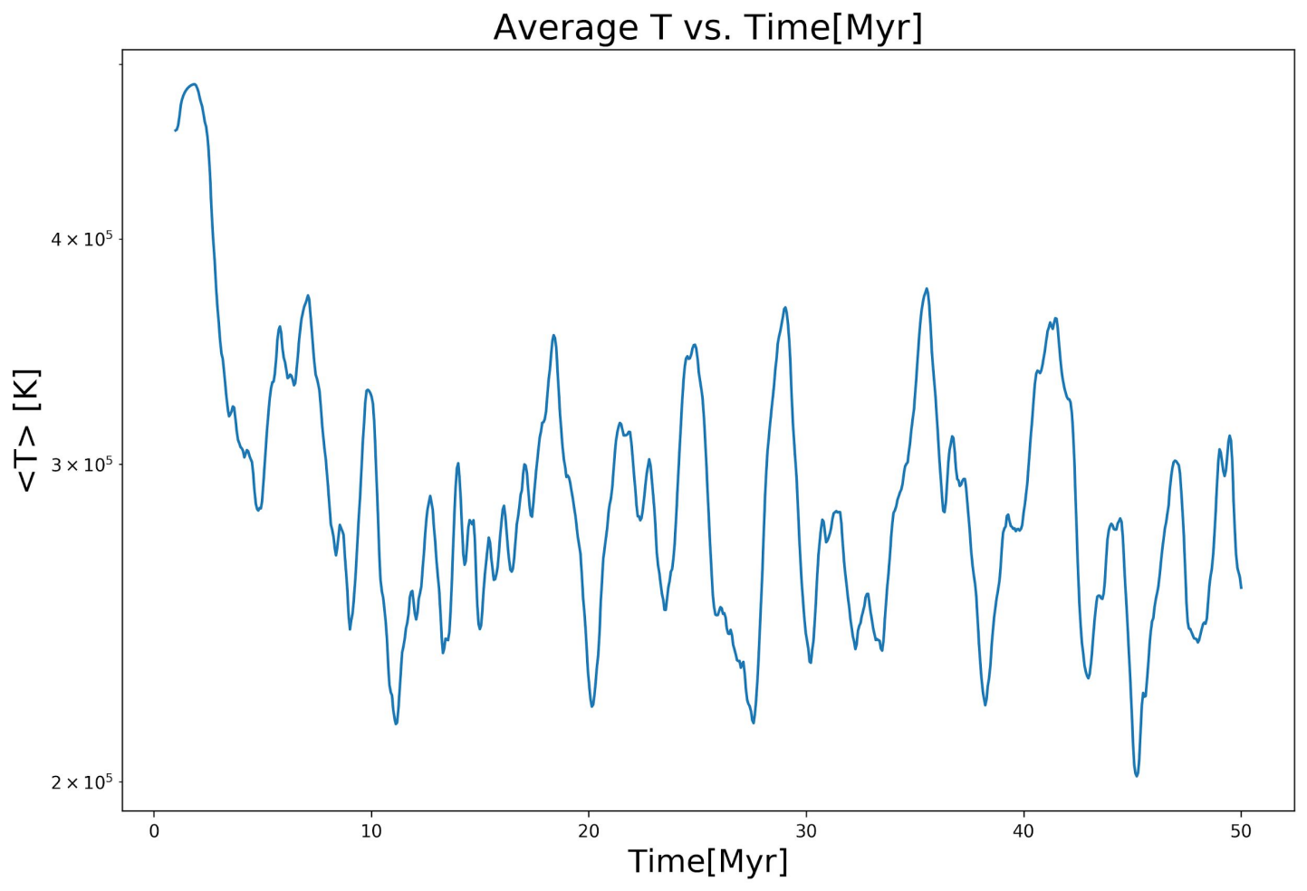

Figure 3: This graph shows the average temperature over time of the first simulation. The temperature is volume weighted.

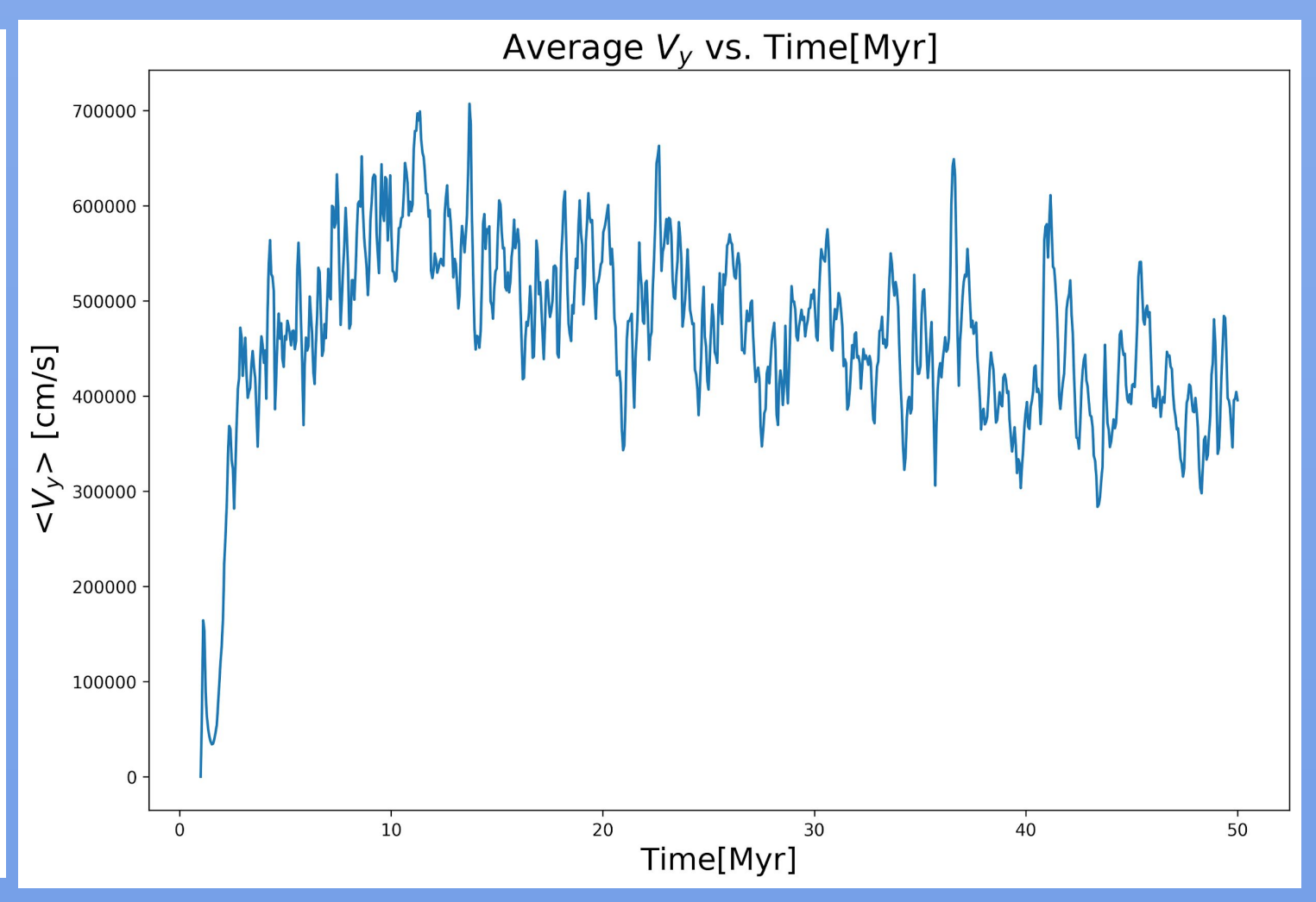

Figure 4: This graph shows the average velocity in the y direction over time for the first simulation. This is also volume weighted.

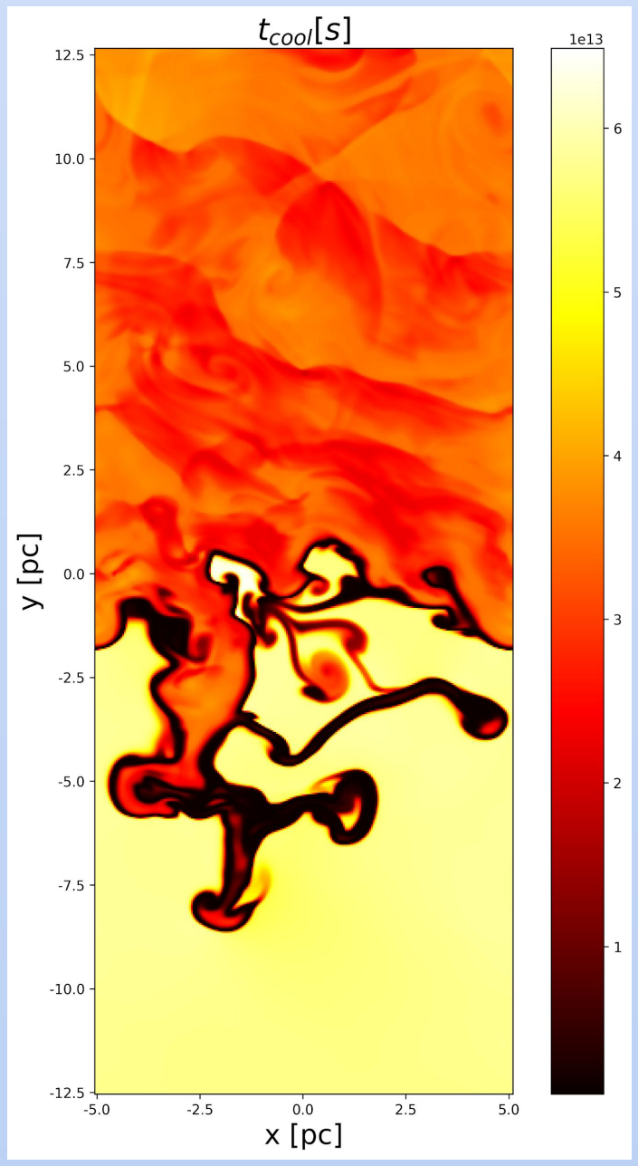

Figure 5: Here is a plot of a timestep of the simulation showing the cooling time (time it takes to cool the gas to 0 K)

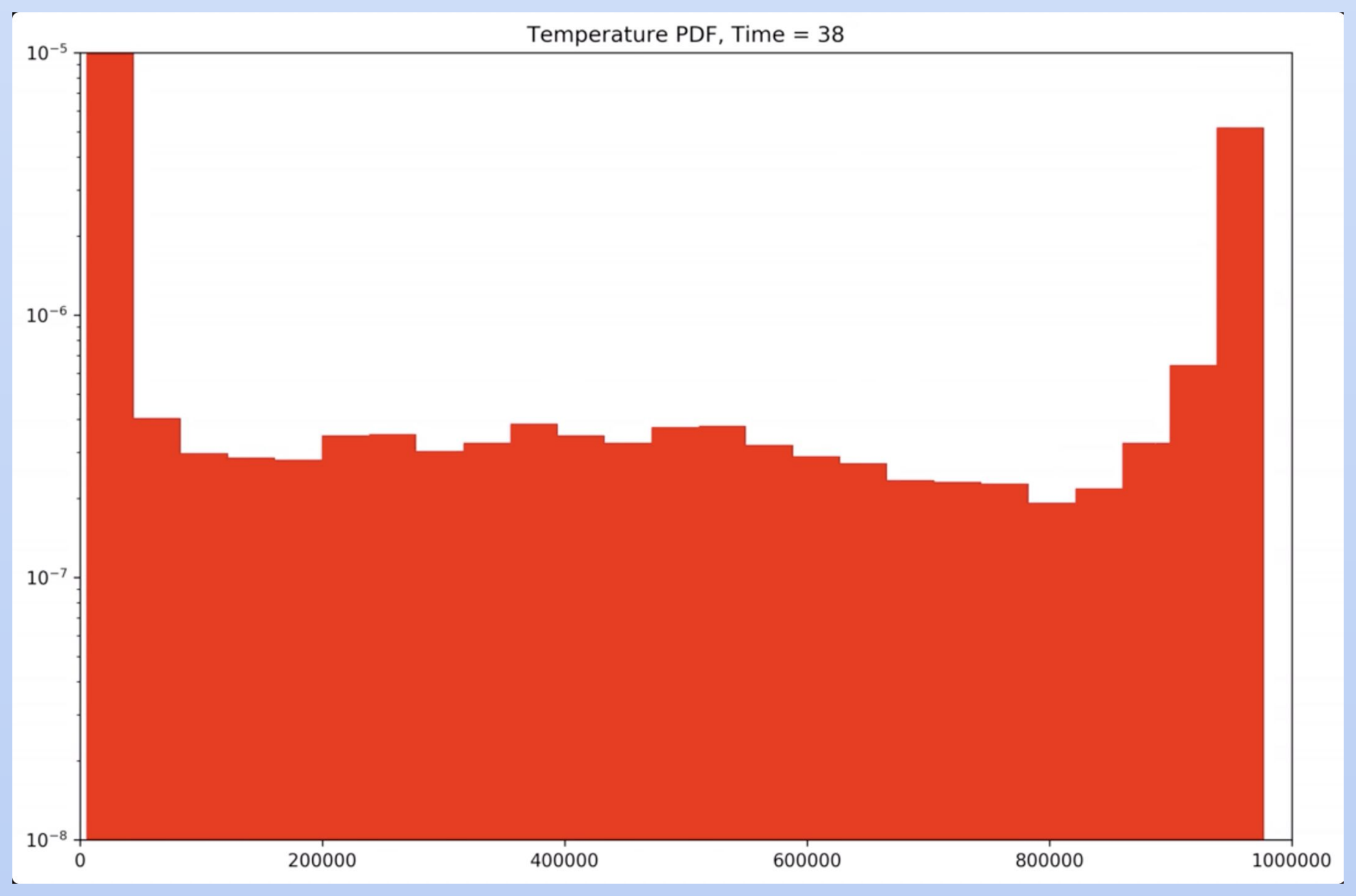

Figure 6: A probability density plot of temperature in K. There is a large probability of the temperature being in the 10^5 K range predicted by the mixing layers. The PDF is weighted by volume. Time = 38 corresponds to the 38th frame in our simulated simulation, an arbitrary fram was chosen, this PDF looks very similar for most frames except for the end frames.

Limitations

Unfortunately, due to constraints this semester we were not able to acquire the tools needed to run a full scale three-dimensional simulation of mixing layers. To do so would require access to some computational servers with greater computing power than a standard laptop. We had to scale down to a two-dimensional simulation because of this.

In doing a two-dimensional simulation we lose a small amount of physics that would typically affect the results. In the actual Interstellar Medium and the universe these gases are in a large three-dimensional region where gas particles are coming from not only the x and y directions but also the z direction, which would affect how the mixing layer forms to a small degree. Our work is only a large approximation to a slice of what is physically occurring

Future Work

We would have loved to explore what factors help create a strong or weak mixing layer but due to the pandemic our group suffered productivity and was not able to accomplish this. In future expansions of this project it would be worthwhile to explore the effects of magnetic fields, viscosity, and different mean molecular weights on the mixing layer.

We also did not have access to a heavy amount of computing power this year so we were not able to run a full scale 3D simulation which makes our results a little less physically applicable.

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