One-Dimensional Models of Turbulent Radiative Mixing Layers in Galactic Winds and the Circumgalactic Medium

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Scientific Background

- Many astrophysical systems, including galactic winds on the pc scale and the circumgalactic medium on the kpc scale, show evidence for cold, dense clouds embedded within a hot, diffuse gas flows.
- These two phases interact through turbulent radiative mixing layers at their interfaces, which controls whether the clouds grow via radiative cooling, or are destroyed by mixing.

Goals

- Model how hot and cold gas in pressure and thermal equilibrium move relative to each other.
- Develop an analytic framework to construct a one-dimensional model for turbulent radiative mixing layers that reproduce salient characteristics of the more computationally expensive 3D simulations, including the mass flux from hot to cold ($j \equiv \rho v_z$) and the cooling distribution.
- Make predictions of spectral emission and absorption features of the gas at intermediate temperatures and compare with observations.

Method

- Numerically integrate the fluid equations to solve for the structure of the 1D mixing layer.
- Introduce a shear velocity that we call v_x and use a prescribed cosine profile for it. We assume that ρ, v_z, and T are in steady state.

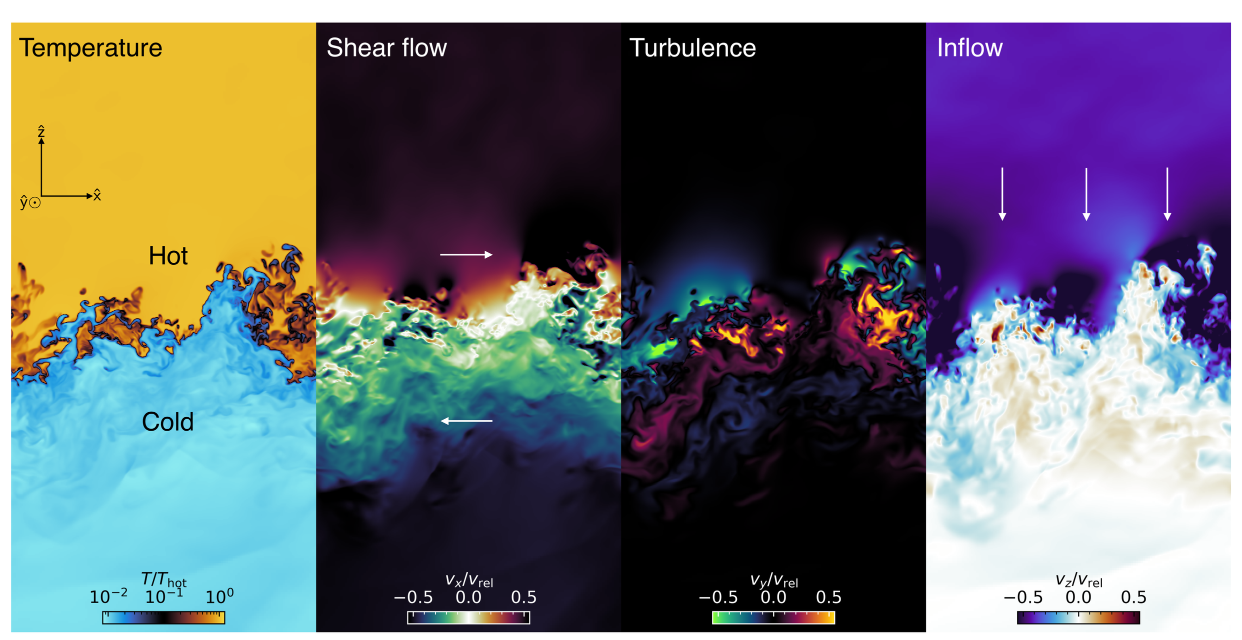

Figure 1: A schematic figure for the mixing layer from a 3D simulation, showing the temperature and the shear, turbulent, and inflow velocities.

Radiative Cooling

- We introduce a cooling function with two equilibria at the two ends of the mixing layer and an intermediate peak, which mimics the cooling rate of gas in galactic winds and in the CGM.
- This cooling function is characterized by 3 quantities: the location of the peak ($T_{\rm peak}$) and the two power law slopes.
- ΔT, the temperature difference between the two equilibria, is a parameter that we are free to adjust, in galactic winds and the CGM ΔT ranges from $\sim 10^2$ K to more than 10^4 K.

Key Parameters of the Mixing Layer

Effective minimum cooling time ($t_{\rm cool,eff}$)

Within the mixing layer, the vast majority of gas is either at very hot or very cold temperatures, where cooling is negligible. This means the horizontally averaged temperature ($\langle T \rangle$) does not reflect amount of rapidly cooling material, as shown in Figure 2.

To account for this in our 1D model, we introduce an effective cooling time $t_{\rm cool,eff}$, defined as:

$$t_{\rm cool,eff} = t^{\beta}_{\rm cool,min}\left(\frac{h}{v_{\rm rel}}\right)^{1-\beta} \quad (1)$$

where we can adjust β between 0 and 1.

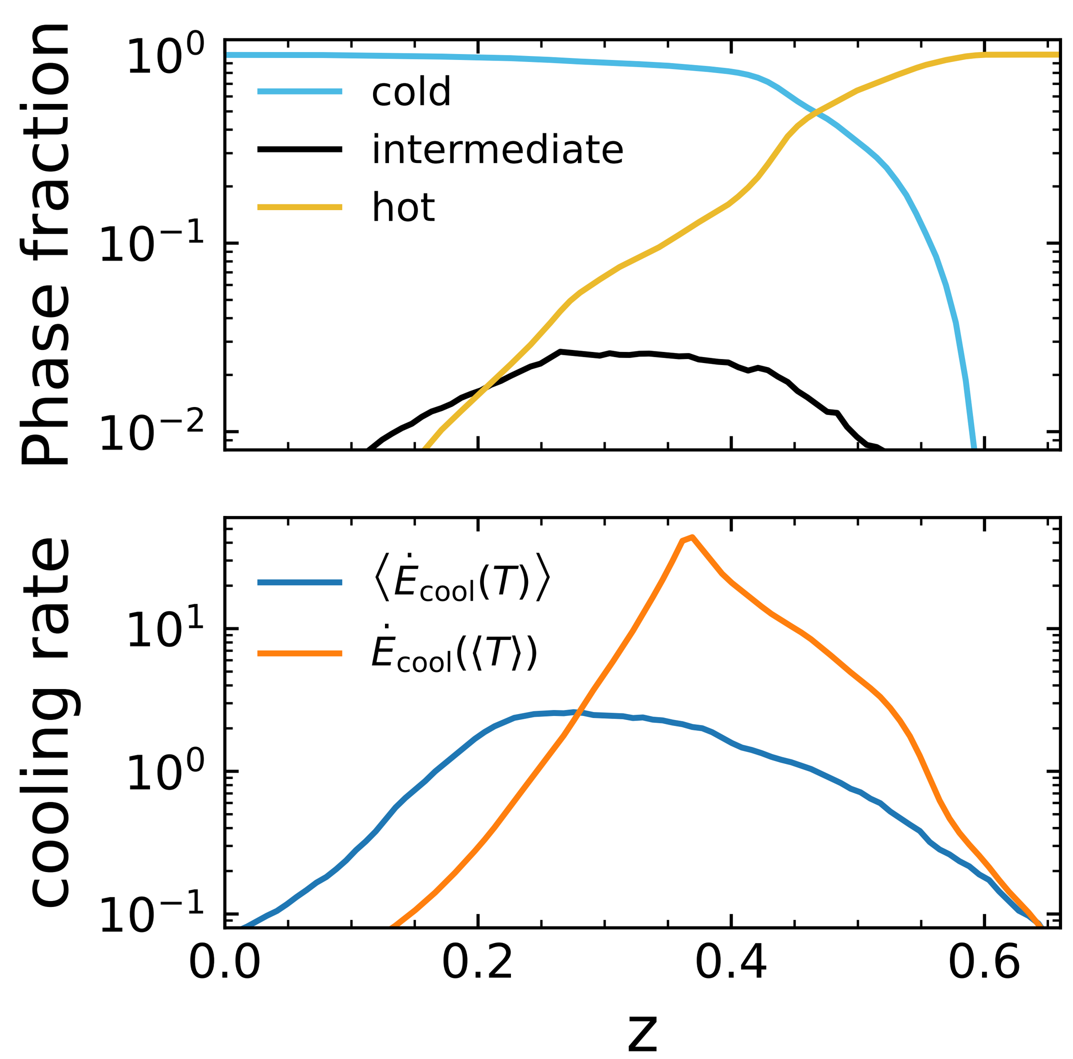

Figure 2: (**Top**) Fraction of cold, intermediate, and hot gas as a function of position in the 3D simulation shown in Figure 1. Only the intermediate temperature material cools appreciably. (**Bottom**) Comparison of the average cooling rate $\langle \dot{E}_{\rm cool} \rangle$ to the cooling rate of the average temperature $\dot{E}_{\rm cool}(\langle T \rangle)$, which highlights that multiphase nature of the gas must be accounted for to capture the correct cooling rate.

Diffusivity

We introduce a temperature dependent conductivity (κ) and viscosity (μ) that capture the effect of turbulent mixing

$$\kappa = f_\nu \, \rho \, v_{\rm rel} \, h \left(\frac{T}{T_{\rm peak}}\right)^{\alpha} \qquad \mu = \Pr \kappa \quad (2)$$

where f_ν is a constant prefactor.

Other constant parameters

- $\Delta T, \Delta v_x, h$ (width of the mixing layer)

Solving Using a Bisection Method on the Mass Flux

- After specifying values of all the parameters, we numerically integrate a system of differential equations obtained from the fluid equations to find a solution.
- There is only one eigenvalue of j that produces a solution that is smooth ($\frac{dT}{dz}=0$) at both hot and cold temperatures. To find this eigenvalue, we apply recursive bisection on j.

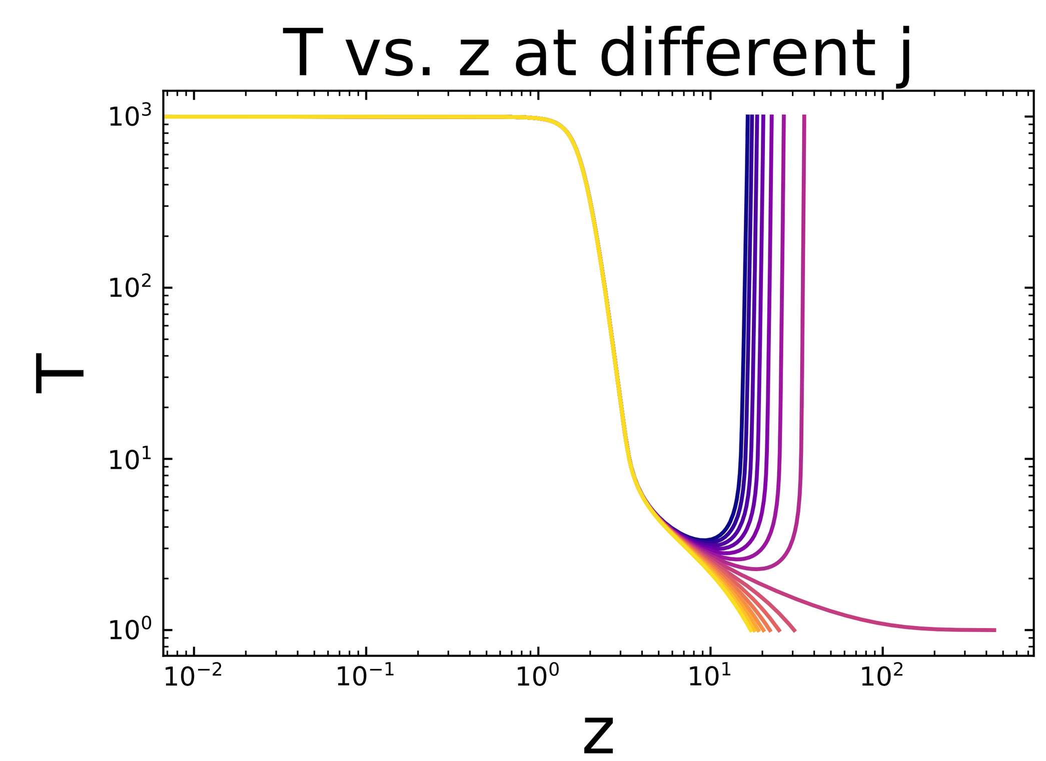

Figure 3: Temperature profiles at different j, j varies around the eigenvalue by $\pm 0.1\%$, lighter color corresponds to smaller j

- The shape of the temperature profile is extremely sensitive to the value of j. Our bisection method resolves the eigenvalue of j to an accuracy of 1 part in 10^{15}, which is approximately equivalent to the accuracy needed to insert a thread on the Earth to the eye of an needle on the Sun.

Mass Flux and Total Cooling

- By rearranging the fluid equations and integrating, we obtain the following relationship between energy sources and sinks:

$$j\left(\frac{\gamma}{\gamma-1}\Delta T\right) = -Q_{\rm cool} + \mathcal{H}_{\rm visc} + \mathcal{W} \quad (3)$$

where j is the mass flux, $Q_{\rm cool}$ is the total cooling, $\mathcal{H}_{\rm visc}$ is the viscous heating term, and $\mathcal{W}$ is the work done by the pressure gradient.

- $\mathcal{H}_{\rm visc}$ and $\mathcal{W}$ are generally much smaller than the other two terms.

Matching the 3D simulations

- We focus our attention on matching 3 quantities: the power slopes of the cooling distribution at high and low temperature (an observable), and the total amount of cooling.
- We have 3 "knobs" to tune in order to get a match: α, β, and f_ν.
- α and β allows us to adjust for the power law slopes without changing the peak position of the cooling distribution by too much.

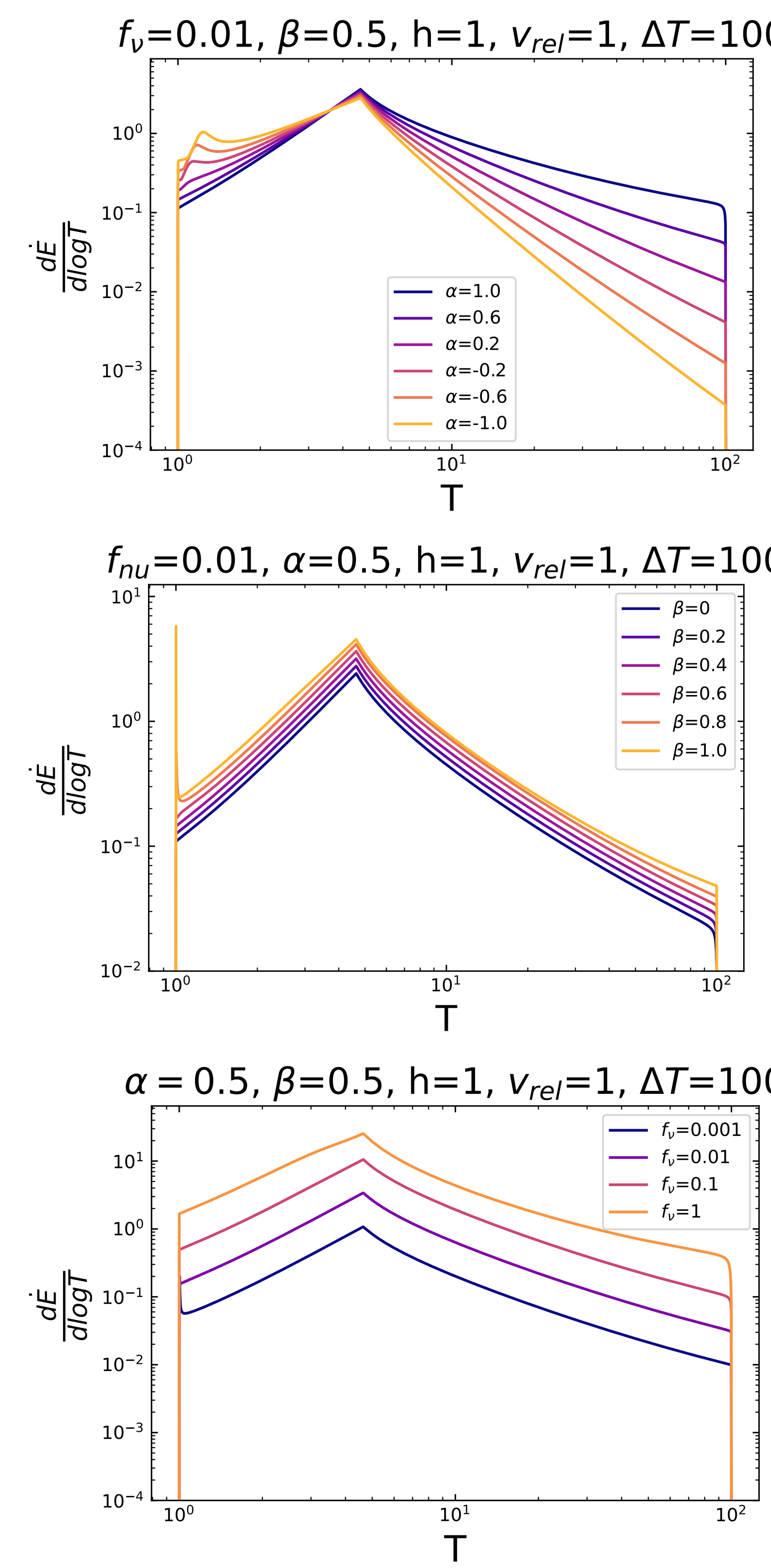

Figure 4: (**Top**) Demonstrates the effect of changing α, (**Middle**) effect of changing β, and (**Bottom**) effect of changing f_ν. Highlights that α primarily controls the shape of the $\dot{E}_{\rm cool}$ distribution and f_ν adjusts for the height of the cooling distribution and thus the mass flux j.

Next Steps

- Find combination of parameters (in particular, α, β, and f_ν) that best fits the mass flux (j) and cooling distribution ($\frac{d\dot{E}}{d\log T}$) of the simulations.
- Predict emission line features from the cooling distribution ($\frac{d\dot{E}}{d\log T}$) of our solution and compare with observation.