Adding Radiation Diffusion to Enzo

Geoffrey So, University of California San Diego,

ISCR, John Hayes,

Lawrence Livermore National Laboratory,

Enzo is a multi-physics fluid dynamics code designed for simulations of structure formation in the early universe. We are implementing a multi-group radiation diffusion module in Enzo so that the reionization of the universe by the first generation of stars can be modeled self-consistently. We present the first results of verification problems used to test the diffusion module and assess its accuracy.

Introduction:

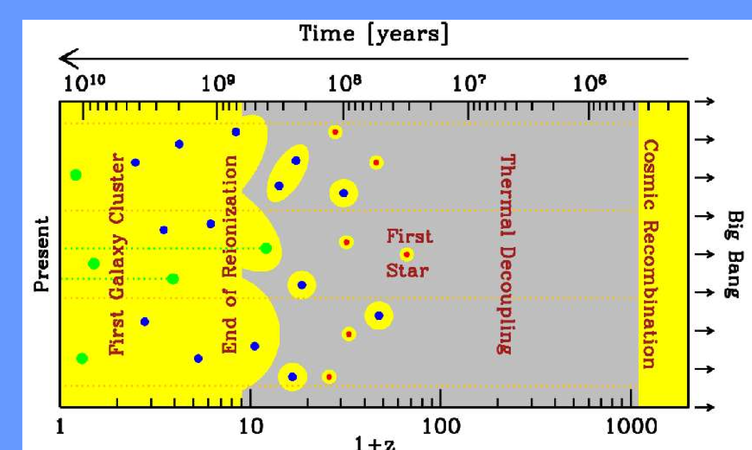
* Enzo can already take into account gravitation, hydrodynamics, and chemistry.

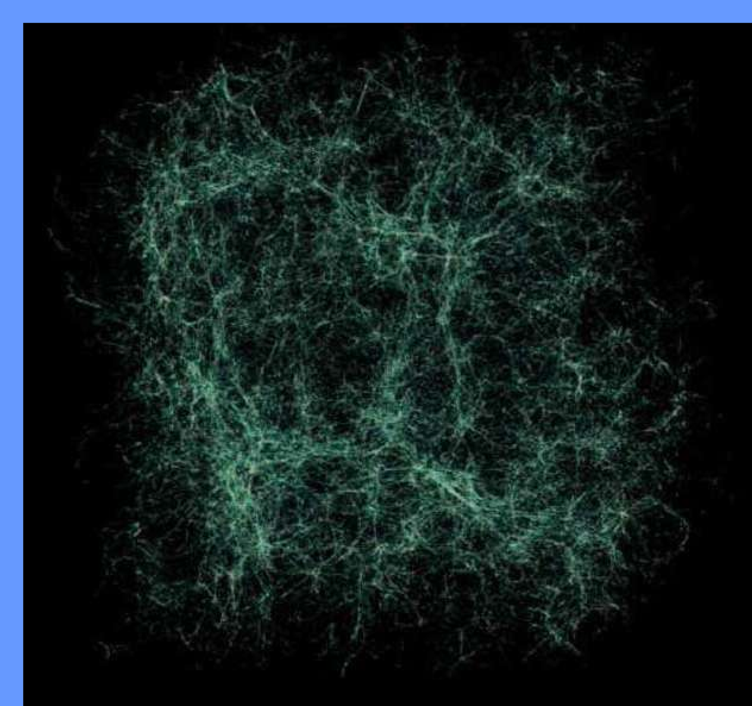
* The work here is to implement the radiation diffusion module written by Dan Reynolds as a portion of Enzo.

* We are showing results of verification tests with analytic solutions.

* This work is ongoing; future tests are shown at the lower right.

* This work is a part of the LUSciD (LLNL-UCSD Scientific Data management) contract with UCOP.





Methods:

The first three equations are the usual conservation of mass, momentum, and energy respectively, the new added terms, equations 3, and 4 (highlighted) are the chemistry and radiation energy equations.

Coupled Matter-Radiation System

Combining the original, cosmological hydrodynamic system with the chemical and radiation equations, we consider the coupled system,

$$\partial_t \rho_b + \tfrac{1}{a}\mathbf{v}_b \cdot \nabla \rho_b = -\tfrac{1}{a}\rho_b \nabla \cdot \mathbf{v}_b,$$

$$\partial_t \mathbf{v}_b + \tfrac{1}{a}(\mathbf{v}_b \cdot \nabla)\mathbf{v}_b = -\tfrac{\dot a}{a}\mathbf{v}_b - \tfrac{1}{a\rho_b}\nabla p - \tfrac{1}{a}\nabla\phi,$$

$$\partial_t e + \frac{1}{a}\mathbf{v}_b \cdot \nabla e = -\tfrac{2\dot a}{a}e - \tfrac{1}{a\rho_b}\nabla\cdot(p\mathbf{v}_b) - \tfrac{1}{a}\mathbf{v}_b\cdot\nabla\phi + G - \Lambda,$$

$$\partial_t \mathbf{n}_i + \nabla\cdot(\mathbf{n}_i\mathbf{v}_b) = -3\tfrac{\dot a}{a}\mathbf{n}_i - \mathbf{n}_i\Gamma_i^{ph} + \alpha_{i,j}^{rec}\mathbf{n}_e\mathbf{n}_j,$$

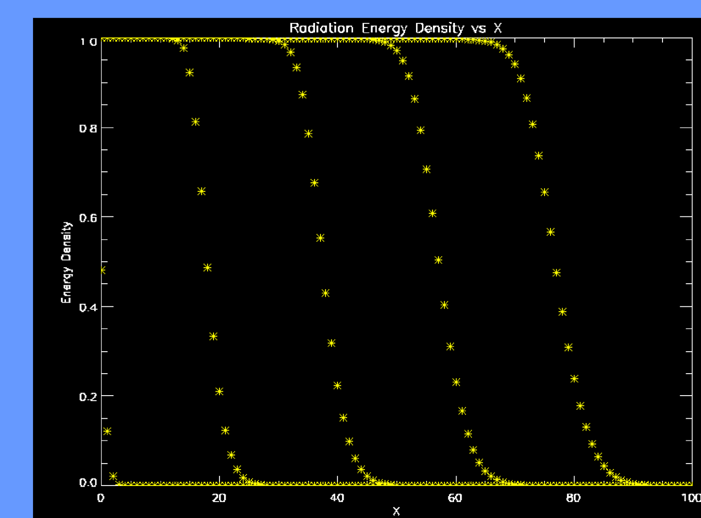
$$\partial_t E + \tfrac{1}{a}\nabla\cdot(E\mathbf{v}_b) - \tfrac{1}{a^2}\nabla\cdot(D\,\nabla E) - \tfrac{1}{ca^3}(\nabla(D\,\nabla E)) : (\nabla\mathbf{v}_b) = -4\tfrac{\dot a}{a}E + 4\pi\eta - ckE.$$

In the fluid energy equation, G is the heating rate and Λ is the combined cooling rate, corresponding to energy sources and sinks due to radiation and chemical couplings.

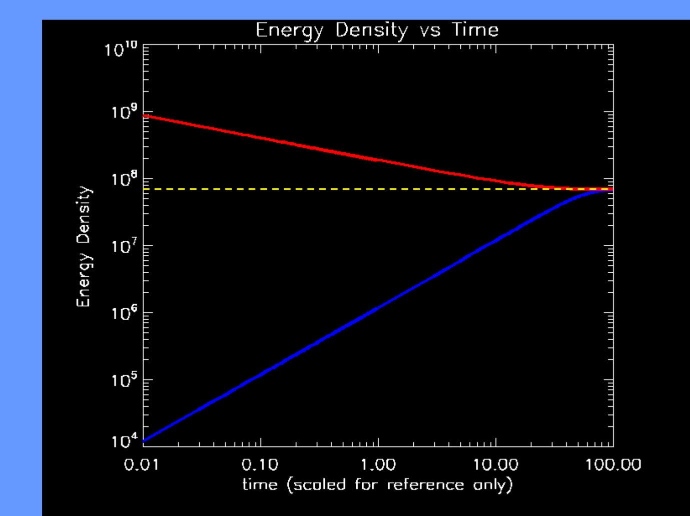
With the new terms in equation 3 and the addition of 4 and 5, Enzo can now simulate the effects that coupled radiation and chemistry have on the surrounding medium.

(figure courtesy of Dr. D. Reynolds)

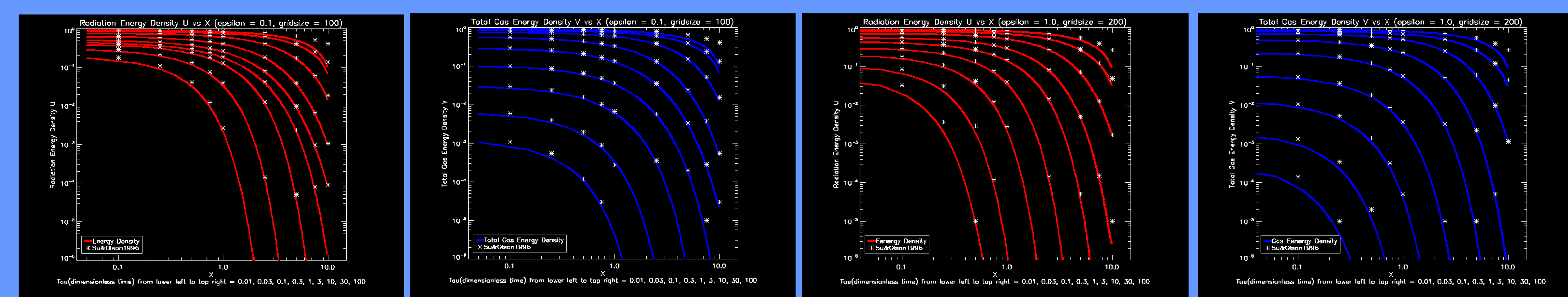
Results:



Radiation Stream test, radiation propagating in the X direction.



Turner&Stone tests, red started with higher, blue started with lower, both asymptotic to the expected value.



This is the 1996 Su & Olson test problem. These show the dimensionless energy variables versus length as defined by Su & Olson.

Future Tests

* Radiating Shocks

* Ionization fronts in static media

* Ionization fronts in moving media

* Multi-group radiation diffusion

* Suggestions are welcomed!

References

* Su and Olson, JQSRT Vol. 56, 1996

* Turner and Stone, APJ Sup 135, 2001

* Barkana and Loeb, AstroPh 0611541v2, 2007

* Jena, et al, MNRAS 361, 2005

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

UCRL-POST-233334