Entropy-based artificial viscosity stabilization for non-equilibrium Grey Radiation-Hydrodynamics

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Outline

Background and Motivation
Development of entropy-based artificial viscosity for the GRHD
Numerical results
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Grey Radiation-Hydrodynamics
A Brief Review of the Entropy Viscosity Method for Conservation Laws

Grey Radiation-Hydrodynamics (GRHD)

GRHD system of equations

$$\partial_t (\rho) + \partial_x (\rho u) = 0$$

$$\partial_t (\rho u) + \partial_x (\rho u^2 + P) = -\partial_x \left(\frac{\epsilon}{3}\right)$$

$$\partial_t (\rho E) + \partial_x [u (\rho E + P)] = -\frac{u}{3}\partial_x \epsilon - \sigma_a c (aT^4 - \epsilon)$$

$$\partial_t \epsilon + \frac{4}{3}\partial_x (u\epsilon) = \frac{u}{3}\partial_x \epsilon + \partial_x \left(\frac{c}{3\sigma_t}\partial_x \epsilon\right) + \sigma_a c (aT^4 - \epsilon)$$

- ρ material density
- u material velocity
- E material specific total energy
- ϵ radiation energy density
- P material pressure
- T material temperature

A few remarks:

- Relaxation term in the energy and radiation equations: $\sigma_a c (aT^4 - \epsilon)$.
- Diffusion term: $\partial_x \left(\frac{c}{3\sigma_t}\partial_x \epsilon\right)$.
- The above system of equations is NOT hyperbolic.

Proposed goal

To stabilize the above system with a high-order artificial viscosity method based on the local entropy production

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Quick overview of the entropy-based artificial viscosity formalism

General scalar conservation law: $\boxed{\partial_t u + \vec{\nabla} \cdot \vec{f}(u) = 0}$.

1. Add viscous fluxes $\boxed{\partial_t u + \vec{\nabla} \cdot \vec{f}(u) = \vec{\nabla} \cdot \mu \vec{\nabla} u}$

2. Let the amount of **artificial viscosity** μ be $\propto$ the **local entropy production**
   - Determine an entropy pair $(s(u), \vec{\Psi}(u))$ for the PDE under consideration
   - Compute the entropy residual $\boxed{R_e := \partial_t s(u_h) + \vec{\nabla} \cdot \Psi(u_h)}$, in each cell K, at each quadrature point x_q
   - Compute the speed and kinematic **entropy viscosity** associated with this residual

$$v_e^K(x_q) := h_K \frac{|R_e(x_q)|_K}{|s - \bar{s}|_\infty} \quad \text{and} \quad \mu_e^K(x_q) := h_K v_e^K(x_q) \tag{1}$$
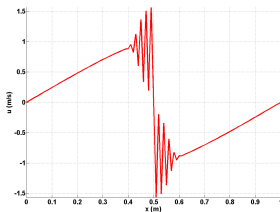
3. Limit the viscosity upper bound to the **Local Lax-Friedrichs** (LLF) viscosity

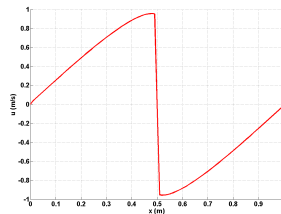$$\mu^K(x_q) := \min\left(\frac{h_K}{2} \max_{x \in K} |\vec{f}'(u(x))|, \mu_e^K(x_q) \right) \tag{2}$$

4. Plug in the standard Galerkin weak form as a viscous regularization

$$\int_V \left(\partial_t u_h + \vec{\nabla} \cdot \vec{f}(u_h) \right) b \, dx + \sum_K \int_K \mu^K \vec{\nabla} u_h \vec{\nabla} b \, dx = 0 \quad \forall b \tag{3}$$

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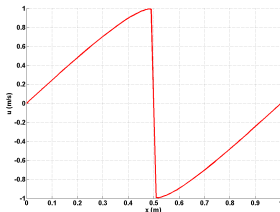A Brief Review of the Entropy Viscosity Method for Conservation Laws

Example: Burgers equation $\partial_t u + \frac{1}{2}\partial_x u^2 = 0$
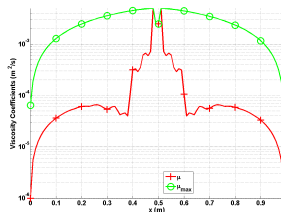

(a) Without stabilization

(b) With first-order viscosity

(c) With entropy viscosity

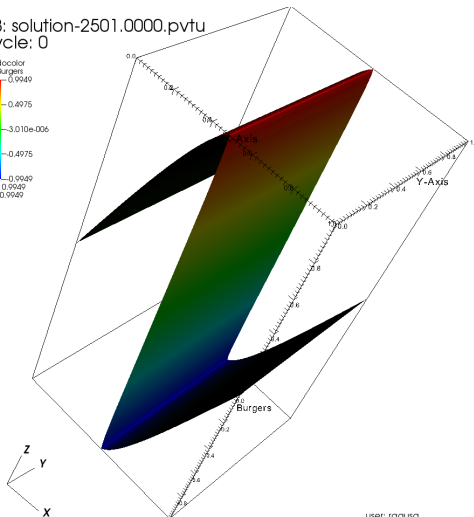(d) Viscosity coefficient profiles

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Viscous regularization of Euler equations

Regularized Euler equations

$$\partial_t \rho + \vec{\nabla} \cdot (\rho \vec{u}) = \vec{\nabla} \cdot \vec{f}$$

$$\partial_t (\rho \vec{u}) + \vec{\nabla} \cdot (\rho \vec{u} \otimes \vec{u} + P \mathbb{I}) = \vec{\nabla} \cdot \mathfrak{g}$$

$$\partial_t (\rho E) + \vec{\nabla} \cdot [\vec{u} (\rho E + P)] = \vec{\nabla} \cdot \vec{h}$$

How to select the artificial viscous fluxes?

By proving that the regularized equations satisfy a minimum principle on the specific entropy, $s(\rho, e)$ [Guermond/Popov/Pasquetti (JCP 2011)]

Minimum entropy principle

$$\inf_{x \in \mathbb{R}^d} s(x, t) \geq \inf_{x \in \mathbb{R}^d} s_0(x) \qquad \forall t \geq 0 \tag{5}$$

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General idea of the derivation

Goal: To obtain an entropy relationship: $\rho(\partial_t s + \vec{u} \cdot \vec{\nabla} s) = \ldots \geq 0$

Entropy is a function of density ρ and internal energy e. Using chain rule, we have

$$\partial_\alpha s = s_\rho \partial_\alpha \rho + s_e \partial_\alpha e \quad \text{with } \alpha = t, x$$

Now, re-write Euler equations in non-conservative form as a function of ρ, u, and e.

Entropy equation

The following choice of viscous fluxes, $\vec{f} = \kappa \vec{\nabla} \rho$, $\mathfrak{g} = \mu \rho \vec{\nabla}^s \vec{u} + \vec{u} \otimes \vec{f}$, and $\vec{h} = \kappa \vec{\nabla}(\rho e) - \frac{1}{2} u^2 \vec{f} + \mathfrak{g} \cdot \vec{u}$, yields:

$$\rho \left(\partial_t s + \vec{u} \cdot \vec{\nabla} s \right) = \vec{\nabla} \cdot \left(\rho \kappa \vec{\nabla} s \right) - \kappa \rho \mathbf{Q} + s_e \mu \vec{\nabla}^s \vec{u} : \vec{\nabla} \vec{u}$$

Quadratic form

$$\mathbf{Q} = X^t \Sigma X \quad \text{with } X = \begin{bmatrix} \vec{\nabla} \rho \\ \vec{\nabla} e \end{bmatrix} \text{ and } \Sigma = \begin{bmatrix} \partial_\rho(\rho^2 \partial_\rho s) & \partial_{\rho,e} s \\ \partial_{\rho,e} s & \partial_{e,e} s \end{bmatrix}$$

The form $\mathbf{Q}$ is negative definite if and only if $-s$ is convex with respect to e and ρ^{-1}.

QED (recall: $s_e = 1/T > 0$)

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Euler equations with viscous regularization (final form)

$$\partial_t \rho + \vec{\nabla} \cdot (\rho \vec{u}) = \vec{\nabla} \cdot \left(\kappa \vec{\nabla} \rho \right)$$

$$\partial_t (\rho \vec{u}) + \vec{\nabla} \cdot (\rho \vec{u} \otimes \vec{u} + P \mathbb{I}) = \vec{\nabla} \cdot \left(\mu \rho \vec{\nabla}^s \vec{u} + \kappa \vec{u} \otimes \vec{\nabla} \rho \right)$$

$$\partial_t (\rho E) + \vec{\nabla} \cdot [\vec{u} (\rho E + P)] = \vec{\nabla} \cdot \left(\kappa \vec{\nabla} (\rho e) + \frac{1}{2} ||\vec{u}||^2 \kappa \vec{\nabla} \rho + \rho \mu \vec{u} \vec{\nabla} \vec{u} \right)$$

where κ and μ are positive viscosity coefficients.

Definition of the viscosity coefficients

- As before, $\mu = \min(\mu^{LLF}, \mu^{entr})$ and $\kappa = \min(\kappa^{LLF}, \kappa^{entr})$
- Entropy viscosities $\propto$ entropy production
- All-speed (from low-Mach to supersonic) extension by Delchini/Ragusa/Berry in Computers & Fluids, 2015

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Entropy-based artificial viscosity technique for the GRHD

Questions to answer:

1. The GRHD equations are not hyperbolic. Can we apply the entropy viscosity method (EVM)?
   - Initial attempt: apply the EVM to we first applied the hyperbolic part of the GRHD [an idea similar to Balsara JQSRT 1999, Lowrie&Morel JQSRT 2001]

2. What is an appropriate functional form for the entropy of the GRHD, $s(\rho, e, \epsilon) = \ldots???$

3. What is an appropriate expression for the viscous fluxes so that the regularized GRHD eqs satisfy the minimum entropy principle?

4. Is the viscous regularization well-behaved in the equilibrium-diffusion limit?

Hyperbolic part of the GRHD

$$\partial_t (\rho) + \partial_x (\rho u) = 0 \tag{7a}$$

$$\partial_t (\rho u) + \partial_x \left(\rho u^2 + P + \frac{\epsilon}{3} \right) = 0 \tag{7b}$$

$$\partial_t (\rho E) + \partial_x \left[u (\rho E + P) \right] + \frac{u}{3} \partial_x \epsilon = 0 \tag{7c}$$

$$\partial_t \epsilon + \frac{4}{3} \partial_x (u \epsilon) - \frac{u}{3} \partial_x \epsilon = 0 \tag{7d}$$

Eigenvalues

$$\lambda_{1,4} = u \pm c_m$$

$$\lambda_{2,3} = u$$

with

$$c_m^2 = \underbrace{P_\rho + \frac{P}{\rho^2} P_e}_{} + \underbrace{\frac{4\epsilon}{9\rho}}_{}$$

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Entropy-based artificial viscosity for the GRHD: derivation

Study of the hyperbolic parts of the GRHD: process

1. Add viscous regularization (fluxes) to the equations

$$\partial_t(\rho) + \partial_x(\rho u) = \partial_x f \tag{8a}$$

$$\partial_t(\rho u) + \partial_x\left(\rho u^2 + P + \frac{\epsilon}{3}\right) = \partial_x g \tag{8b}$$

$$\partial_t(\rho E) + \partial_x[u(\rho E + P)] + \frac{u}{3}\partial_x\epsilon = \partial_x(h) \tag{8c}$$

$$\partial_t\epsilon + \frac{4}{3}\partial_x(u\epsilon) - \frac{u}{3}\partial_x\epsilon = \partial_x\ell \tag{8d}$$

2. With $s(\rho, e, \epsilon)$, use chain rule to obtain the entropy relationship

$$\partial_\alpha s = \partial_\rho s \partial_\alpha \rho + \partial_e s \partial_\alpha e + \partial_\epsilon s \partial_\alpha \epsilon \tag{9}$$

3. Simplify the expression by assuming $s(\rho, e, \epsilon) = s_{Euler}(\rho, e) + s_{rad}(\rho, \epsilon)$

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Study of the hyperbolic parts of the GRHD: results

1

$$s(\rho, e, \epsilon) = s_{Euler}(\rho, e) + \frac{4a^{1/4}}{3\rho} \epsilon^{\frac{3}{4}} \quad (10)$$

2 Using the Eulerian viscous fluxes, supplemented by an radiation energy viscous flux

$$\begin{cases} f &= \kappa \partial_x \rho \\ g &= \rho \mu \partial_x u + uf \\ h &= \kappa \partial_x (\rho e) - \frac{1}{2} u^2 f + gu \\ \ell &= \kappa \partial_x \epsilon \end{cases} \quad (11)$$

we get the following result:

3 Entropy conservation statement:

$$\rho \frac{Ds}{Dt} = \partial_x (\rho \kappa \partial_x s) + (\kappa \partial_x \rho)(\partial_x s) - \rho \kappa X^T A X + s_e \rho \mu (\partial_x u)^2 \geq 0$$

$$X = \begin{bmatrix} \partial_x \rho \\ \partial_x e \\ \partial_x \epsilon \end{bmatrix} \text{ and } A = \begin{bmatrix} \partial_\rho \left(\rho^2 \partial_\rho s_{Euler} \right) & \partial_{\rho,e} s_{Euler} & 0 \\ \partial_{\rho,e} s_{Euler} & \partial_{e,e} s_{Euler} & 0 \\ 0 & 0 & -\frac{a^{1/4}}{4\rho} \epsilon^{-5/4} \end{bmatrix}$$

The form $X^T A X$ is negative -definite (Delchini/Ragusa/Morel, JCP 2015)

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Entropy conservation statement for the full GRHD equations

recently, we have been able to show:

$$\rho \frac{Ds}{Dt} = \partial_x \left(\rho \kappa \partial_x s \right) + (\kappa \partial_x \rho)(\partial_x s) - \rho \kappa X^T A X + s_e \rho \mu (\partial_x u)^2$$

$$+ \left(\rho s_e - s_e \right) \sigma_a c \left(a T^4 - \epsilon \right) + \rho s_\epsilon \partial_x \left(\frac{c}{3 \sigma_t} \partial_x \epsilon \right) \geq 0 \quad (12)$$

where the terms in red are unconditionally entropy-producing (unpublished, in preparation)

Finally, the Regularized full GRHD equations are:

$$\partial_t \left(\rho \right) + \partial_x \left(\rho u \right) = \partial_x \left(\kappa \partial_x \rho \right) \quad (13a)$$

$$\partial_t \left(\rho u \right) + \partial_x \left(\rho u^2 + P + \frac{\epsilon}{3} \right) = \partial_x \left(\kappa \partial_x (\rho u) \right) \quad (13b)$$

$$\partial_t \left(\rho E \right) + \partial_x \left[u \left(\rho E + P \right) \right] = -\frac{u}{3} \partial_x \epsilon - \sigma_a c \left(a T^4 - \epsilon \right) + \partial_x \left(\kappa \partial_x (\rho E) \right) \quad (13c)$$

$$\partial_t \epsilon + \frac{4}{3} \partial_x \left(u \epsilon \right) = \frac{u}{3} \partial_x \epsilon + \partial_x \left(\frac{c}{3 \sigma_t} \partial_x \epsilon \right) + \sigma_a c \left(a T^4 - \epsilon \right) + \partial_x \left(\kappa \partial_x \epsilon \right) \quad (13d)$$

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Equilibrium Diffusion Limit

non-dimensionalization:

$$\partial_{t'}\left(\rho'\right) + \partial_{x'}\left(\rho'u'\right) = \mathbb{V}_\infty \partial_x \left(\kappa' \partial_{x'} \rho'\right) \tag{14a}$$

$$\partial_{t'}\left(\rho'u'\right) + \partial_{x'}\left(\rho u^{2'} + P' + \mathbb{P}_\infty \frac{\epsilon'}{3}\right) = \mathbb{V}_\infty \partial_{x'}\left(\kappa' \partial_{x'}(\rho'u')\right) \tag{14b}$$

$$\partial_{t'}\left(\rho'E'\right) + \partial_{x'}\left[u'\left(\rho'E' + P'\right)\right] = -\mathbb{P}_\infty \frac{u'}{3}\partial_{x'}\epsilon'$$
$$- \mathbb{P}_\infty \mathbb{C}_\infty^{-1}\mathbb{L}_\infty \left(\sigma'_t - \mathbb{L}_{s,\infty}\sigma'_s\right)\left(T'^{,4} - \epsilon'\right) + \mathbb{V}_\infty \partial_{x'}\left(\kappa' \partial_{x'}(\rho'E')\right) \tag{14c}$$

$$\partial_{t'}\epsilon' + \frac{4}{3}\partial_{x'}\left(u'\epsilon'\right) = \frac{u'}{3}\partial_{x'}\epsilon' + \mathbb{L}_\infty^{-1}\mathbb{C}_\infty^{-1}\partial_{x'}\left(\frac{1}{3\sigma'_t}\partial_{x'}\epsilon'\right)$$
$$+ \mathbb{C}_\infty^{-1}\mathbb{L}_\infty \left(\sigma'_t - \mathbb{L}_{s,\infty}\sigma'_s\right)\left(T'^{,4} - \epsilon'\right) + \mathbb{V}_\infty \partial_{x'}\left(\kappa' \partial_{x'}\epsilon'\right) \tag{14d}$$

non-dimensional parameters

$$\mathbb{L}_\infty = L_\infty \sigma_{t,\infty} = \mathcal{O}(\varepsilon^{-1}), \ \mathbb{L}_{s,\infty} = \frac{\sigma_{s,\infty}}{\sigma_{t,\infty}} = \mathcal{O}(\varepsilon), \ \mathbb{C}_\infty = \frac{c_{m,\infty}}{c} = \mathcal{O}(\varepsilon)$$

$$\mathbb{P}_\infty = \frac{aT_\infty^4}{\rho_\infty c_{m,\infty}^2} = \mathcal{O}(1), \ \mathbb{V}_\infty = \frac{\kappa_\infty}{c_{m,\infty}L_\infty} = \mathcal{O}(1)$$

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We variables is expanded in a power series in ε

Equilibrium Diffusion Limit results:

$$\partial_t \rho_0 + \partial_x (\rho u)_0 = \partial_x (\kappa \partial_x \rho)_0 \tag{15a}$$

$$\partial_t (\rho u)_0 + \partial_x (\rho u^2 + P^*)_0 = \partial_x (\kappa \partial_x (\rho u))_0 \tag{15b}$$

$$\partial_x (\rho E^*)_0 + \partial_x [u (\rho E^* + P^*)]_0 = \partial_x \left(\frac{1}{3\sigma_t} \partial_x T^4\right)_0 + \partial_x (\kappa \partial_x \rho E^*)_0 \tag{15c}$$

$P^* = P + \mathbb{P}_\infty \frac{T^4}{3}$ and $E^* = E + \mathbb{P}_\infty \frac{T^4}{\rho}$

Leading order of entropy

$$s_0 (\rho, e) = s_{Euler,0} (\rho, e) + \frac{4}{3} \frac{T_0^3}{\rho_0} \tag{16}$$

We recover the EDL results.
Viscous regularization scales adequately.

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Temperature-dependent opacities

Numerical solution

- spatial discretization: CFEM
- temporal discretization: fully implicit (BDF2)
- solution technique: JFNK with finite-difference approximation of the Jacobian as preconditioner
- semi-analytical solutions provided by Jim Fergusson
- Two sets of results presented today:
  1. with constant opcacities (Mach 1.05, 2, 5, 50)
  2. with temperature-dependent opacities (Mach 3)
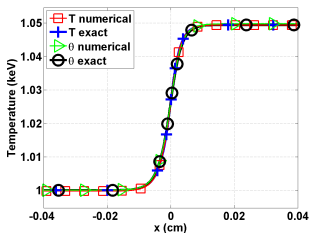
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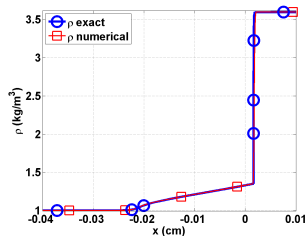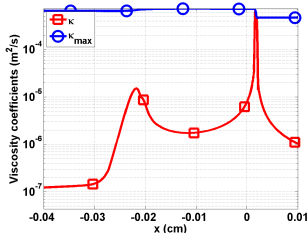
Steady-state solution for Mach 1.05

(a) Temperatures

(b) Material density

(c) Viscosity coefficients

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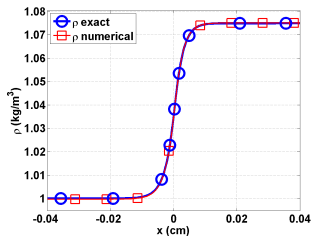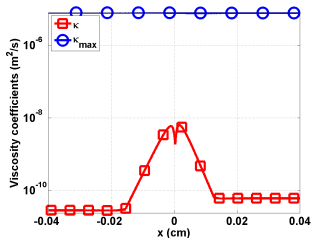
Steady-state solution for Mach 2

(a) Temperatures

(b) Material density

(c) Viscosity coefficients

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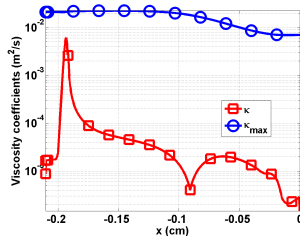**Constant opacities**
Temperature-dependent opacities
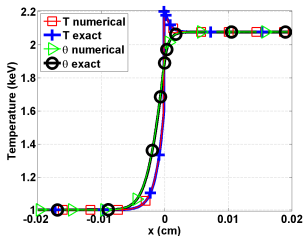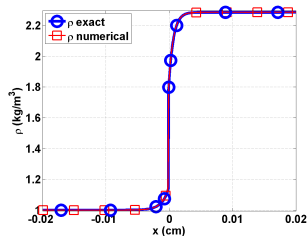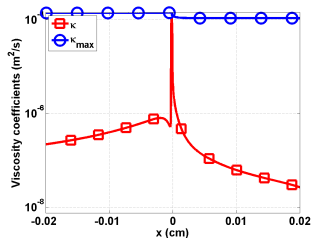
Steady-state solution for Mach 5
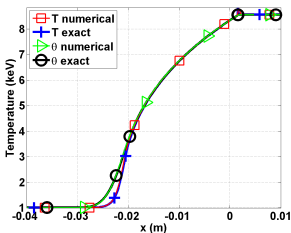
(a) Temperatures

(b) Material density

(c) Viscosity coefficients

(d) Zoom at the Z spike
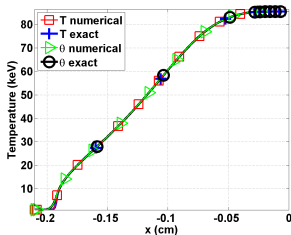
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Steady-state solution for Mach 50

(a) Temperatures

(b) Material density

(c) Viscosity coefficients

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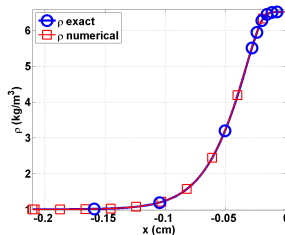
Steady-state solution for Mach 3: density, 500 cells

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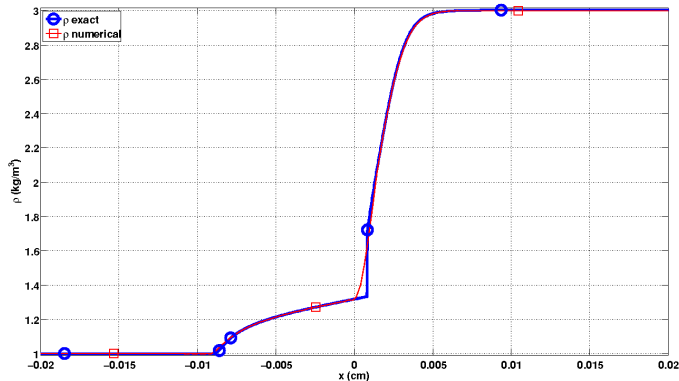
Steady-state solution for Mach 3: density, 1000 cells

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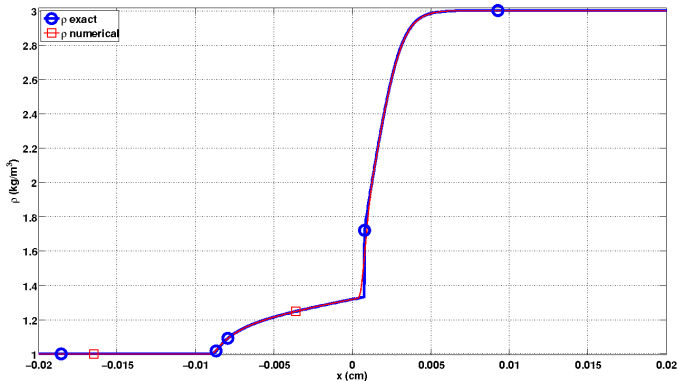
Steady-state solution for Mach 3: density, 2000 cells

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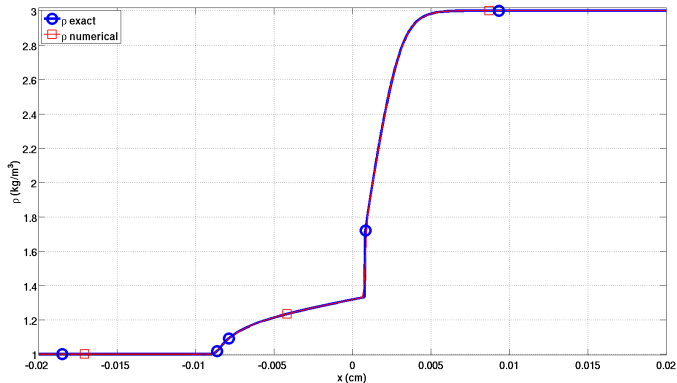
Steady-state solution for Mach 3: temperature, 500 cells

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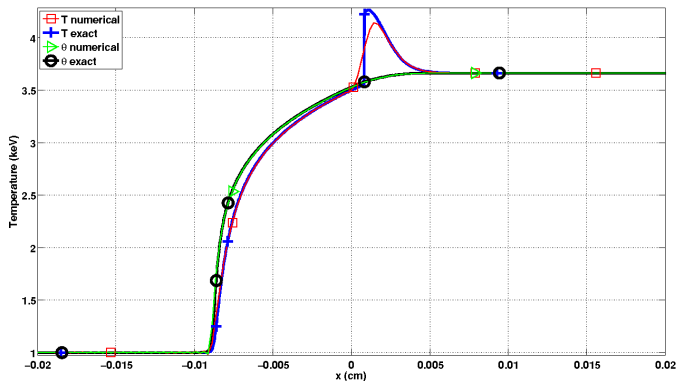
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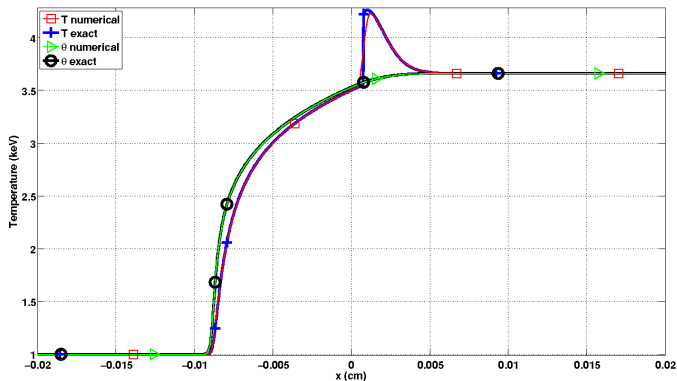
Steady-state solution for Mach 3: temperature, 2000 cells

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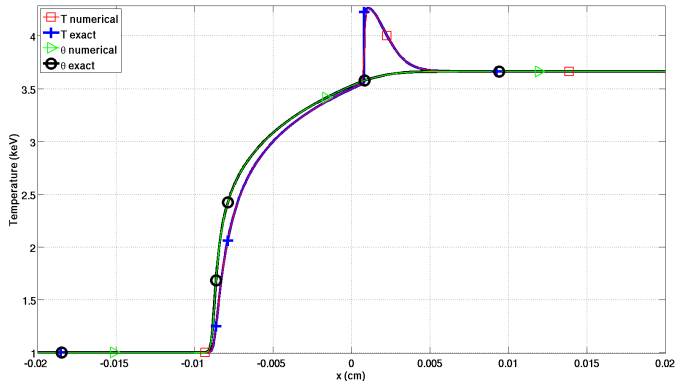
Steady-state solution for Mach 3: viscosity, 500 cells

Background and Motivation
Development of entropy-based artificial viscosity for the GRHD
Numerical results
Conclusions

Constant opacities
Temperature-dependent opacities
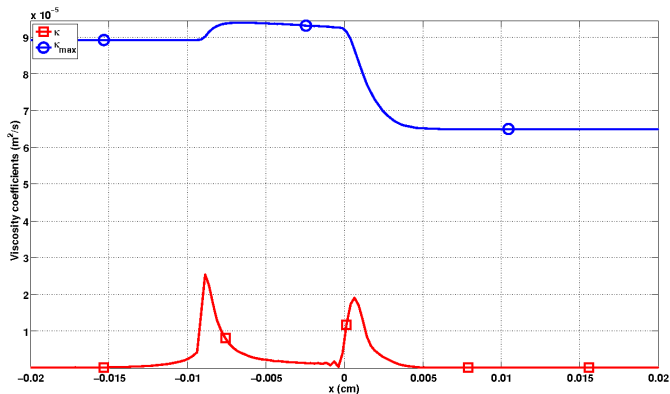
Steady-state solution for Mach 3: viscosity, 1000 cells

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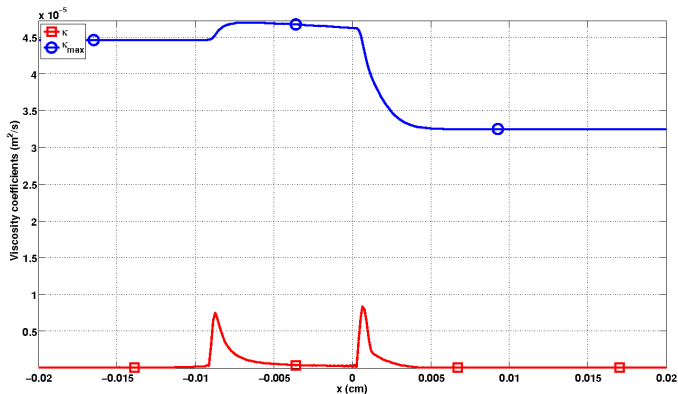
# Steady-state solution for Mach 3: viscosity, 2000 cells
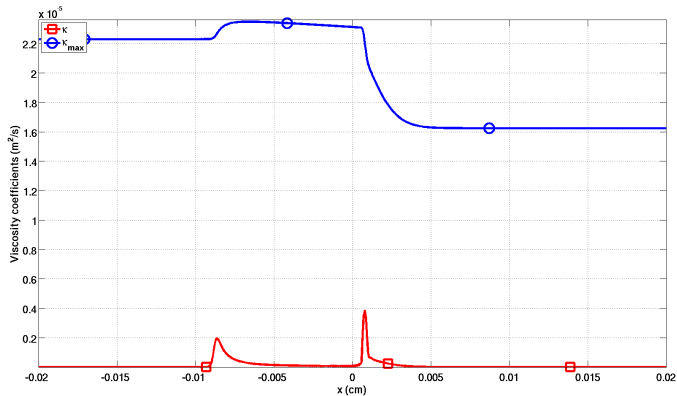
Conclusions

- Extended the entropy-viscosity method to full Grey Radiation-Hydrodynamic equations
- Verified entropy minimum principle for regularized equations
- Viscous regularization scales appropriate in the equilibrium-diffusion limit
- Numerical results are in excellent agreement with semi-analytical solutions

Outlook

- Multi-D
- Replace radiation diffusion with S_n radiation transport
- switch solution technique to IMEX
- DGFEM spatial discretization

Thank you
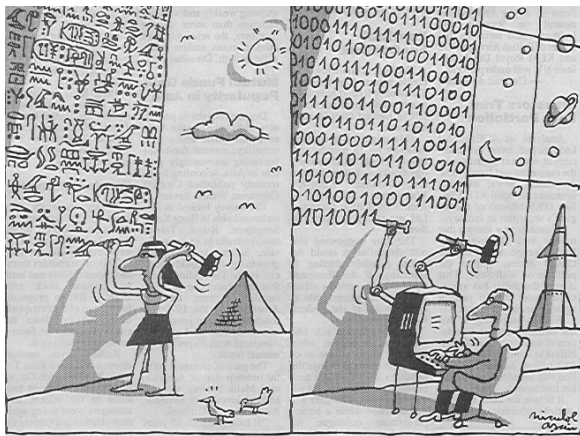
Thank you.

Why an upper bound for viscosity?

[noframenumbering]

Large entropy residual in shocks $\longrightarrow$ large entropy viscosity μ_e

There is such a thing as too much of a good thing ...
Il ne faut point être plus royaliste que le Roy

Upper bound for μ

First-order upwind scheme is monotone but over dissipative. We should not exceed the amount of stabilization that such a scheme provides.

upwinding = centered approximation (Galerkin) − numerical diffusion
Example: linear advection $\partial_t u + \beta \partial_x u = 0$

$$\beta \frac{u_i - u_{i-1}}{h} = \beta \frac{u_{i+1} - u_{i-1}}{2h} - \frac{\beta h}{2} \frac{u_{i+1} - 2u_i + u_{i-1}}{h^2} \tag{17}$$

So, the dissipative term is $\frac{\beta h}{2} \partial_{xx} u$ and the first-order viscosity is $\frac{\beta h}{2}$

First-order viscosity

- scalar conservation law: $\frac{h}{2}|f'(u)|$ • system: $\frac{h}{2} \max\left(\text{eig}(\partial_u f)\right)$