Detecting shock waves in SPH simulations

“Simulations with Gadget”
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Shock waves in galaxy clusters

1E 0657-56 ("Bullet cluster")
(NASA/SAO/CXC/M.Markevitch et al.)

Abell 3667
(Radio: Australia Telescope Comp. Array. X-ray: ROSAT/PSPC.)
Motivation

- **cosmological shocks** dissipate gravitational energy into thermal gas energy
- **shock waves are tracers** of the large scale structure and contain information about its dynamical history (**warm-hot intergalactic medium**)
- **shocks accelerate energetic particles** (**cosmic rays**) through diffusive shock acceleration at structure formation shocks
- **cosmic ray injection** by supernova remnants (when combined with radiative dissipation and star formation)
- **shock-induced star formation** in the interstellar medium

This work: Christoph Pfrommer, Volker Springel, Torsten Enßlin, & Martin Jubelgas, MNRAS submitted
Idea

- SPH shock is broadened to a scale of the order of the smoothing length $h$, i.e. $f_h h$, and $f_h \sim 2$
- approximate instantaneous particle velocity by pre-shock velocity (denoted by $v_1 = \mathcal{M}_1 c_1$)

Using the **entropy conserving formalism** of Springel & Hernquist 2002 ($A(s) = P \rho^{-\gamma}$ is the entropic function):

$$\frac{A_2}{A_1} = \frac{A_1 + dA_1}{A_1} = 1 + \frac{f_h h}{\mathcal{M}_1 c_1 A_1} \frac{dA_1}{dt} = \frac{P_2}{P_1} \left( \frac{\rho_1}{\rho_2} \right)^\gamma$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1) \mathcal{M}_1^2}{(\gamma - 1) \mathcal{M}_1^2 + 2}$$

$$\frac{P_2}{P_1} = \frac{2\gamma \mathcal{M}_1^2 - (\gamma - 1)}{\gamma + 1}$$
Complications

1. Broad Mach number distributions $f(\mathcal{M}) = \frac{du}{dt\,d\log \mathcal{M}}$
   because particle quantities within the (broadened) shock front do not correspond to those of the pre-shock regime.
   \textbf{Solution}: introduce decay time $\Delta t_{\text{dec}} = f_{\text{h}}h/(\mathcal{M}_1c)$, meanwhile the Mach number is set to the maximum (only allowing for its rise in the presence of multiple shocks).

2. Weak shocks imply large values of $\Delta t_{\text{dec}}$:
   \textbf{Solution}: $\Delta t_{\text{dec}} = \min[f_{\text{h}}h/(\mathcal{M}_1c), \Delta t_{\text{max}}]$

3. Strong shocks with $\mathcal{M} > 5$ are slightly underestimated because there is no universal shock length.
   \textbf{Solution}: recalibrate strong shocks!
How to use the shock finder:

Switches:

- **-DMACHNUM**: Mach number master switch
- **-DMACHSTATISTIC**: output of $\frac{d\varepsilon_{\text{diss}}(a)}{d\log a}$
- **-DCR_OUTPUT_JUMP_CONDITIONS**: output of density and thermal energy jump at shocks in the case of cosmic rays

Parameters:

- **Shock\_LengthScale** = $f_h \approx 2.0$
- **Shock\_DeltaDecayTimeMax** = $\Delta t_{\text{max}} \approx 0.0025$
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Shock tube: Mach number statistics

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Detecting shock waves in SPH simulations – p.9/12
Shock tube (CRs & gas)

Detecting shock waves in SPH simulations
Cosmological simulation

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