Galactic Physics near the Resolution Scale

Gasoline / ChaNGa SPH (James Wadsley/Tom Quinn)

James Wadsley (McMaster)
Ben Keller (McMaster), Tom Quinn (Washington)

Gadget-2 (Volker Springel)

Visualization by Andrew Pontzen/pynbody

$t/t_{KH} = 3.50$
Gasoline
Blob Test (Agertz et al. 2007)

$t/t_{KH} = 3.50$

ChaNGa SPH (James Wadsley/Tom Quinn)

Gadget-2 (Volker Springel)

Blob Test (Agertz et al. 2007)
Agertz et al 2007

Code comparison paper from the proto AstroSim conference (2004)

Gasoline (Wadsley, Stadel & Quinn 2004)

Gadget (Springel)

FLASH

ENZO

ART
Agertz et al 2007
Code comparison paper from the proto AstroSim conference (2004)

SPH
Smoothed Particle Hydrodynamics
(Monaghan 1992, Springel & Hernquist 2002)

PPM
Piecewise Parabolic Method
(Collela & Woodward 1987)
Agertz (2007) Basic Result: SPH blobs don’t break up

Immediate SPH issue: Surface Tension present in arithmetic sum Pressure force (e.g. Monaghan 1992, Gadget 2, ...)

Suppresses Kelvin Helmholtz instabilities

Issue first identified by Ritchie & Thomas (2001)
SPH Kelvin Helmholtz fixes

• Ritchie & Thomas (2001) – smooth pressure not density and Geometric Density Average in Force: remove surface tension (pressure spike at density jump)
• Price (2008) – smear density jumps
• Solutions typically expensive (more accurate) but see also Hopkins (2013)
Key to alleviating SPH surface tension:

- **Geometric Density Average in Force (GD Force):**

\[
\frac{dv_a}{dt} = -\sum_b m_b \left( \frac{P_a + P_b}{\rho_a \rho_b} \right) \nabla_a W_{ab}
\]

Morris (1996), Monaghan (1992), Ritchie and Thomas (2001),
Can be derived from a Lagrangian:
Monaghan & Rafiee (2012)
see also Abel (2011), Hopkins (2013)
Is removing surface tension enough?

Blob Test in Entropy ($T^{3/2}/\rho$)

Hi-Res ENZO

Hi-Res Old SPH
Blob Test in Entropy \( (T^{3/2}/\rho) \)

Is removing surface tension enough? No
Blob Test in Entropy ($T^{3/2}/\rho$)

ENZO

Old SPH

GD Force SPH

\[ t = 1.25 \tau_{KH} \quad t = 2.5 \tau_{KH} \quad t = 3.75 \tau_{KH} \]
Blob Test in Entropy ($T^{3/2}/\rho$)

$t = 1.25 \tau_{KH}$

$t = 2.5 \tau_{KH}$

$t = 3.75 \tau_{KH}$

Low Entropy Blobs Indestructible!
The second issue: Mixing

Cluster Comparison (Frenk et al 1999)

Grid codes have entropy cores, SPH codes don’t (because they don’t mix)

Wadsley, Veeravalli & Couchman (2008)
How to get entropy cores?

• Shocks (while $c_s < v$)
• Mix hot & cold cluster gas

SPH can’t:

$$\frac{du}{dt} = -(\gamma - 1) u(\nabla \cdot v) \Rightarrow A(s) = \frac{P}{\rho^\gamma} = \text{const.}$$

Eulerian codes can (accidentally):

$$\frac{\partial u}{\partial t} + v \cdot \nabla u + \text{advection errors} = -(\gamma - 1) u(\nabla \cdot v)$$
Subgrid Turbulent Mixing

- Fluid elements on a fixed (resolved) physical scale do exchange energy/entropy due to unresolved (turbulent) motions

\[
\frac{\partial \bar{u}}{\partial t} + \bar{v} \cdot \nabla \bar{u} = - (\gamma - 1) u (\nabla \cdot v) \quad \text{goes to}
\]

\[
\frac{\partial \bar{u}}{\partial t} + \bar{v} \cdot \nabla \bar{u} + \overline{\delta v \cdot \nabla \delta u} = - (\gamma - 1) \left( \bar{u} (\nabla \cdot v) + \overline{\delta u (\nabla \cdot \delta v)} \right)
\]

where \( a = \) resolved (filtered) part of field \( a \),
\[
\delta a = \text{unresolved part}, \quad \overline{\delta a} = 0
\]

Turbulent diffusive heat flux
Turbulent diffusion

- Lowest-order turbulent diffusion model:
  \[
  \frac{\partial \bar{u}}{\partial t} + \bar{v} \cdot \nabla \bar{u} = - (\gamma - 1) \bar{u} (\nabla \cdot \bar{v}) + \nabla \kappa_{Turb} \nabla \bar{u}
  \]
  
  \(\kappa_{Turb}\) has units of velocity x length

Smagorinsky model (1963):
  \[\kappa_{Turb} = l_s^2 S, \quad S = \sqrt{S_{ij} S_{ij}}\]

\(S_{ij}\) = strain tensor of resolved flow, \(l_s\) Smagorinsky length

Incompressible grid models set \(l_s^2 \sim 0.02 \Delta x^2\) (Lilly 1967)

For SPH we can use \(\kappa_{Turb} = C h^2 S\) \(C \sim 0.01-0.1\)

Wadsley, Veeravalli & Couchman (2008)
Shen, Wadsley & Stinson (2010)
Turbulent diffusion

- Cluster Entropy Cores occur in SPH when thermal diffusion included.
- Need: Galilean invariance, correct Prandtl numbers
- Not clear that grid advection errors give correct solution!

Wadsley, Veeravalli & Couchman (2008)
Shen, Wadsley & Stinson (2010)
Blob Test in Entropy ($T^{3/2}/\rho$)
Blob Test in Entropy ($T^{3/2}/\rho$)

$\text{ENZO}$

$\text{Old SPH}$

$\text{GD Force}$

$\text{Turbulent Diffusion}$

$\text{SPH}$

$t = 1.25 \tau_{KH}$

$t = 2.5 \tau_{KH}$

$t = 3.75 \tau_{KH}$
Is grid (PPM) the right answer?

No: Numerical Diffusion Approximate, e.g. is not Galilean Invariant

ENZO Moving flow

ENZO 1/2 – 1/2

ENZO Moving blob

t = 1.25 \tau \text{KH}

t = 2.5 \tau \text{KH}

t = 3.75 \tau \text{KH}
Blob’s falling apart... (Log)

- Old SPH
- Old SPH + Diffusion
- GDForce SPH
- ENZO (1/2 each)
- ENZO Moving blob
- ENZO Moving flow (Agertz et al.)
- GD Force + Diffusion
- Coefficient 0.1, 0.03, 0.01
10^{11} Solar Mass Galaxy (Gasoline) Fabio Governato
Large scale gas accretion similar, but overall star formation higher cf. Teyssier: Better mixing $\rightarrow$ intermediate T $\rightarrow$ more cooling
Fabian: SPH surface tension a feature! Anticipating MHD effects!
Deriving SPH: The f factor

Originally introduced in Springel & Hernquist (2002), Hopkins (2013) form:

\[ f_{ij} = 1 - \frac{\dot{x}_j}{x_j} \left( \frac{h_i}{3\tilde{y}_i} \frac{\partial y_i}{\partial h_i} \right) \left[ 1 + \frac{h_i}{3\tilde{y}_i} \frac{\partial \tilde{y}_i}{\partial h_i} \right]^{-1} \]

What does f actually do?

For adiabatic gas, PdV work

\[ \frac{du}{dt} = -\frac{P}{\rho} \nabla \cdot \mathbf{v} = (\gamma - 1) \frac{u}{\rho} \frac{d\rho}{dt} \]

In an arbitrary SPH formulation this isn’t true and can even be systematically wrong

f corrects the PdV work to keep \( u \propto \rho^{\gamma-1} \)

And thus conserves entropy. f falls out naturally from the Lagrangian but can be worked out for any SPH
Current Version (2013):

- Fixed number of neighbours (e.g. 64 for Wendland $C_2$ kernel, Dehnen & Aly 2012)
- Single SPH smooth (no iterations)
- Standard density, geometric density forces
- Turbulent Diffusion (Shen, Wadsley & Stinson 2010)
- $f$ correction to PdV work
- Multistepping power of 2 KDK plus Saitoh & Makino (2009) timestep adjustment

Good integrator test: Sedov-Taylor blast in T=0 K gas ($128^3$) 0.08 % Energy error
Planning for the future ...

• CHANGA Tree SPH based on Charm++ language (project lead: Tom Quinn, U. Washington)
• Charm++ includes GPU/CUDA/SSE2 support, automated load balancing, migration, checkpoint
• New CHANGA public release (this summer) will include all GASOLINE SPH updates including corrected force/timesteps/etc... , Stinson et al. (2006) star formation

Aside:

Reducing numerical diffusion in grid codes

Galaxy disk
200 km/s rotation
Gives large advection errors unless you work in a rotating frame

500 pc subregion in model MW galaxy ENZO simulation, 30 pc resolution

- Pick a rotation rate: radii near co-rotation see large benefit
- Need to add coriolis force
- Effective resolution 4x better
- Faster: Courant timesteps much shorter $dt \sim dx/10 \text{ km/s}$ vs. $dx/200 \text{ km/s}$

Benincasa, Tasker, Wadsley & Pudritz (submitted)
• Radiation pressure and UV feedback: pre-process medium around star cluster but self-limiting to roughly $v_{\text{esc \ GMC}} \sim 20$ km/s (for normal galaxies)

• Many stellar feedback ideas based on single supernovae (e.g. Stinson et al. 2006, “blastwave”). Feedback from star clusters is qualitatively different ... 

• Stellar winds and supernovae combine into a super bubble that can drive outflows

(see talks by Lacey, Naab)
Super bubble features

- Star cluster output: winds supernova, shock and thermalize in bubble
- Mechanical Luminosity $L = 10^{38}$ erg/s/10$^4$ Msun
- Thin shell forms quickly: immediately get pressure driven snowplough
- Mass loading of bubble due to evaporation by thermal conduction

MacLow & McCray 1988, Weaver et al 1977, Silich et al 1996
Super bubble features

Superbubbles efficient
Ideal self-similar PDS solution
- Thermal Energy: Eth = 0.45 L t
- Kinetic Energy: Ek = 0.20 L t
- Shell radiative losses: 0.35 L t

Limiting factor: Radiative Cooling of bubble determined by bubble temperature $\sim$ Eth/Mb and density Mb/R$^3$

Hot bubble mass (Mb) set by thermal conduction rate into bubble

MacLow & McCray 1988, Weaver et al 1977, Silich et al 1996
Thermal Conductivity

\[ \frac{\partial E}{\partial t} = \nabla \kappa_{\text{Cond}} \nabla T \quad \kappa_{\text{Cond}} = 6 \times 10^{-7} \ T^{5/2} \text{ (cgs)} \]

- Self regulating Energy flux \( \sim T^{7/2}/L \)
- Translates into mass flow from shell until bubble \( T \) is lowered to \( \sim \) few \( 10^6 \) K (Bubble energy, metals conserved)

High-Res SPH conductivity simulation

Gasoline (method similar to Jubelgas et al 2004)
Super bubble Simulation

9004 kyr
Super bubble Simulation

- SPH: 750 Msun/particle – similar to galaxy sim
- $3 \times 10^4$ Msun star cluster in 1 H/cc, solar metallicity cooling
- 40 star particles
- 10 gas ejecta

50% Feedback efficiency After 30 Myr!
Super bubble Simulation

- Conductive mass loading moderately increases cooling
- 0.65 L t (no bubble cooling)
- 0.55 L t (no conductivity)
- 0.5 L t (conductivity)

Convergence 750 Msun → 94 Msun

Note: Thermal Energy does not include thermal energy of shell or ambient medium
Mass loading

- ~200 shell particles evaporated into bubble
- Bubble temperature regulated at ~2 x 10^6 K
Mass loading

- ~ 200 shell particles evaporated into bubble
- Bubble temperature regulated at ~2 x 10^6 K

Match
Silich et al 1996
Mass loading
For 3x10^38 erg/s
Feedback
Mb ~ 6 M*
Super bubbles: Vishniac Instabilities

5.429 Myr

Nirvana simulations
3 star bubble
Krause et al 2013

Theory: Vishniac 1983
Sims: McLeod & Whitworth 2013, Nayakshin et al 2012 (AGN)
Super bubble Feedback

- Dalla Vecchia & Schaye (2012) showed the importance of moderate feedback mass ($T_{\text{feedback}} > 10^{6.5} \text{ K}$) for effective feedback – but what sets $T_{\text{feedback}}$?
- Can use physical models (conduction) to determine mass loading and $T_{\text{feedback}}$ – one less free parameter!
- No cooling shutoff (at least one free parameter there)
Summary

• All galaxy simulators have to ask: What value do we provide over semi-analytics?
Summary

• All galaxy simulators have to ask: What value do we provide over semi-analytics?
• Not much with 10+ free parameters
• To bridge the gap:
  We need to calibrate our feedback and other models (diffusion, cooling) with small scale, controlled tests NOT final observables