Galaxy formation with SPHS: a novel mode of positive feedback

Alexander Hobbs
ETH Zürich

w. Justin Read (Uni. Surrey), Chris Power (UWA), Andrina Nicola (ETH Zürich)
So what is SPHS?

**SPHS** - Smoothed Particle Hydrodynamics with a higher order dissipation Switch

(Read & Hayfield 2012)
So what is SPHS?

**SPHS** - Smoothed Particle Hydrodynamics with a higher order dissipation Switch
(Read & Hayfield 2012)

Other flavours:  
- Ritchie & Thomas 2001  
- Price 2008  
- Wadsley et al. 2008  
- Cullen & Dehnen 2010  
- Hopkins 2012  
- Kawata et al. 2013a  
- “Anarchy”

‘Classic’ SPH

cf. Springel (2005)
Smoothed particle hydrodynamics (SPH)

- Solves equations of hydrodynamics on interpolation points that move with the flow - ‘particles’

- Advantages include:
  1. Lagrangian
  2. Galilean invariant
  3. Manifestly conservative
  4. Easy to implement
  5. Couples well to N-body approach

- Variable smoothing lengths refine resolution on density
...is great

Figure credit: J. Shaye, OWLS project

Figure credit: D. Price, Monash Uni
...but there are problems to fix

1. Force error in momentum equation
2. Multi-valued fluid quantities preventing mixing of phases
3. Overly viscous
4. Noisy

Kelvin-Helmholtz instability:

Figure credit: Read et al. 2010b
The “blob test”

A 1:10 density ratio gas sphere in a wind tunnel (Mach 2.7), initially in pressure eq.

A study on how AV dampens small scale vorticity was done using the CHARM code. Each frame shows a density slice through the cloud center at time $t=0$.

The standard $\alpha=0$, $\beta=0$ case is most stable, whereas the $\alpha=1$ case is most unstable but it is not clear how physical this solution is. The shock front gets more blurred and we see strong post shock ringing effects. The reason for the increased instability is probably due to unphysical use of the shock capturing. The use of artificial viscosity with densities varying from low (red) to high (blue).

Fig. 11 shows the outcome of the simulations at $t=5$ and $t=10$. We can directly see the impact of lowering viscosity we make the cloud even more unstable but it is not clear how physical this solution is. The shock front gets more blurred and we see strong post shock ringing effects. The reason for the increased instability is probably due to high speed particles traveling through the poorly captured shock region and transferring momentum inside the cloud, perturbing it in an unphysical way.

Table 1 shows the comparison of viscosity values. A simulation using the Balsara switch turns of viscosity where $\tau_{KH}$ is. The shock front gets more blurred and we see strong post shock ringing effects. The reason for the increased instability is probably due to unphysical use of the shock capturing. The use of artificial viscosity with densities varying from low (red) to high (blue).
...but there are problems to fix

1. Force error in momentum equation
2. Multi-valued fluid quantities preventing mixing of phases
3. Overly viscous
4. Noisy
...but there are problems to fix

1. Force error in momentum equation
2. Multi-valued fluid quantities preventing mixing of phases
3. Overly viscous
4. Noisy
...but there are problems to fix

1. Error reduced w. 442 neighbours + stable high-order HOCT kernel

2. Multi-valued fluid quantities preventing mixing of phases

3. Overly viscous

4. Noisy
...but there are problems to fix

1. Error reduced w. 442 neighbours + stable high-order HOCT kernel

2. Multi-valued pressures eliminated using advance warning high order switch and conservative dissipation

3. Overly viscous

4. Noisy
...but there are problems to fix

1. Error reduced w. 442 neighbours + stable high-order HOCT kernel

2. Multi-valued pressures eliminated using advance warning high order switch and conservative dissipation

3. Same high order switch gives lower viscosity away from shocks

4. Noisy
...but there are problems to fix

1. Error reduced w. 442 neighbours + stable high-order HOCT kernel

2. Multi-valued pressures eliminated using advance warning high order switch and conservative dissipation

3. Same high order switch gives lower viscosity away from shocks

4. Larger neighbour number + high-order HOCT kernel gives lower noise

+ Saitoh & Makino (2008) timestep limiter
Multivalued pressures - the problem

Read, Hayfield & Agertz 2010 (RHA10); Read & Hayfield 2012

Friday, 12 July 13
Multivalued fluid quantities - the need for dissipation

$A_1, m_1, \mathbf{v}_1 \ldots A_2, m_2, \mathbf{v}_2 \ldots$
SPHS tests - Sedov-Taylor blast wave

Read & Hayfield 2012
Friday, 12 July 13
SPHS tests - Sedov-Taylor blast wave

SPHS–HCT442; 64³

\[ \rho \]

\[ x \]
SPHS tests - Sedov-Taylor blast wave

Read & Hayfield 2012
Friday, 12 July 13
SPHS tests - Sedov-Taylor blast wave

Read & Hayfield 2012
Friday, 12 July 13
SPHS tests - KH instability 1:8 density contrast
The formation of entropy cores in non-radiative galaxy cluster simulations: SPH versus AMR

C. Power\textsuperscript{1*}, J. I. Read\textsuperscript{2} & A. Hobbs\textsuperscript{3}

\textsuperscript{1}International Centre for Radio Astronomy Research, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia
\textsuperscript{2}Department of Physics, University of Surrey, Guildford, GU2 7XH, Surrey, United Kingdom
\textsuperscript{3}Institute for Astronomy, Department of Physics, ETH Zürich, Wolfgang-Pauli-Strasse 16, CH-8093, Zürich, Switzerland

ABSTRACT
We simulate the formation and evolution of a massive galaxy cluster in a $\Lambda$CDM Universe using three different approaches to solving the equations of hydrodynamics in the absence of radiative cooling: one based on the ‘classic’ Smoothed Particle Hydrodynamics (SPH) method; one based on a novel SPH algorithm with a higher order dissipation switch (SPHS); and one based on an adaptive mesh refinement (AMR) method. We find that SPHS and the AMR code are in excellent agreement with one another: in both, the spherically averaged entropy profile forms a well-defined core that rapidly converges with increasing mass and force resolution.
SPHS science tests - Santa Barbara test


Friday, 12 July 13
SPHS science tests - Santa Barbara test

Redshift $z=0$

$S = \log(T \rho^{-2/3})$

$R [R_{\text{vir}}]$


Friday, 12 July 13
SPHS science tests - Santa Barbara test

see also Wadsley (2008)
...and finally...
Galaxy formation with SPHS
Galaxy formation with SPHS

- Cooling hot gaseous halo (e.g., Kaufmann et al. 2006, 2007, 2009) forming MW
Galaxy formation with SPHS

- Cooling hot gaseous halo (e.g., Kaufmann et al. 2006, 2007, 2009) forming MW

  - Late (smooth) accretion mode corresponding to main disk formation phase
    (Abadi et al. 2003, Sommer-Larsen et al. 2003, Governato et al. 2004)
Galaxy formation with SPHS

- Cooling hot gaseous halo (e.g., Kaufmann et al. 2006, 2007, 2009) forming MW

- Late (smooth) accretion mode corresponding to main disk formation phase
  (Abadi et al. 2003, Sommer-Larsen et al. 2003, Governato et al. 2004)

\[ \rho(r) = \frac{A \text{sech} \left( \frac{r}{r_s} \right)}{(r/r_s)^{7/9} \left[ 1 + (r/r_s)^{4/9} \right]^6} \]

Dehnen & McLaughlin (2005)

\[ M_{\text{halo}} \approx 1.9 \times 10^{12} \, M_{\odot} \]
\[ M_{\text{gas}} \approx 1.9 \times 10^{11} \, M_{\odot} \]

\[ r_t = 200 \, \text{kpc} \quad r_s = 40 \, \text{kpc} \]

\[ T(r) = \frac{\mu}{k_B} \frac{1}{\rho_{\text{gas}}(r)} \int_r^\infty \rho_{\text{gas}}(r) \frac{G M(r)}{r^2} \, dr \]

Mastropietro et al. (2005), Kaufmann et al. (2007)

\[ \lambda_{\text{gas}} = \frac{j_{\text{gas}} |E_{\text{halo}}|^{1/2}}{GM_{\text{halo}}^{3/2}} \]
\[ j_{\text{gas}} \propto r^{1.0} \]
\[ \lambda = 0.038 \]

Peebles 1969, Bullock et al. 2001b
Simulation

ICs relaxed with adiabatic EQS to eliminate Poisson noise
- Using HOCT442 kernel (reduces particle noise)

Radiative cooling
- $T_{\text{floor}} = 100$ K
- Ensure Jeans mass resolved with $M_{\text{res}} = N_{\text{res}} m_{\text{sph}}$

$$\rho_J = \left( \frac{\pi k T}{\mu m_p G} \right)^3 \left( \frac{1}{M_{\text{res}}} \right)^2$$

- $M_{\text{gas}} \approx 4 \times 10^4 M_{\odot}$
- $M_{\text{res}} \approx 5 \times 10^6 M_{\odot}$

Stars form on polytrope above a fixed density threshold

$P = A(s)\rho^{4/3}$

100 atoms cm$^3$
$M \propto j^{2.2}$
\[ j = rv \sin \left[ \sin^{-1} \left( \frac{r}{2r_b} \right) \right] \]
\[ \theta = \sin^{-1} \left( \frac{r}{2r_b} \right) \]
\[ j = rv \frac{r}{2r_b} \]
\[ j = r \left( \frac{2GM(r)}{r} \right)^{1/2} \frac{r}{2r_b} \]
\[ M(r) = Ar \]
\[ j = r(2G)^{1/2} A^{1/2} \frac{r}{2r_b} \]
\[ \therefore \quad j \propto r^2 \]
\[ M \propto \left( \frac{j^{1/2}}{r_s} \right)^{4/9} \]
\[ \therefore \quad M \propto j^{1.1} \]
SPHS-96 | IM

$r_{\text{final}} < 1.0$  
$1.0 < r_{\text{final}} < 2.0$  
$2.0 < r_{\text{final}} < 5.0$  
$5.0 < r_{\text{final}} < 10.0$

Friday, 12 July 13

Hobbs, Read & Nicola, in prep.
In conclusion, we have shown that SPHS:

- Corrects for fundamental limitations in ‘classic’ SPH relating to mixing of multiple phases within the fluid (Agertz et al. 2007)

- Presents a practical method that is not subject to prohibitive numerical cost (Hobbs et al. 2013)

- Forms an entropy core in the SB test (Power, Read & Hobbs 2013) (puts to rest AMR vs. SPH controversy for this problem)

- Eliminates spurious cold clumps in SPH simulations and paves the way toward a new mode of disc feeding (Hobbs et al. 2013)
SNe-driven fragmenting filament

- Qualitatively similar to break-up of ‘cold-mode’ cosmological streams (Keres et al. 2009, Keres & Hernquist 2009)
  - Overdensity allows for non-linear mode of collapse
  - Different progenitors (SNe vs. large-scale cosmological flows)
  - Different scales (50 kpc --> galaxy vs. > 200 kpc --> 40 kpc)
  - Different temperatures ($10^4$ K vs $10^5$ K)

- Form of positive feedback whereby SNe give rise to cold gas flows that feed the disc and fuel further star formation

- Filaments can have preferentially low angular momentum and are efficient at bringing gas from 50 kpc $\rightarrow$ 1 kpc in $t_{\text{ff}}$
What’s next?

- Inclusion of metals (metal line cooling, metal diffusion)
  - may alter condensation of filaments from ambient gas
  - can determine if feeding mode provides a source of pristine gas

- Cos

- n

- s

- SME

- c

- Cas

Feeding supermassive black holes through supersonic turbulence and ballistic accretion

Alexander Hobbs,1* Sergei Nayakshin,2 Chris Power2 and Andrew King2

1 Institute for Astronomy, Department of Physics, ETH Zürich, Wolfgang-Pauli-Strasse 16, CH-8093 Zürich, Switzerland
2 Department of Physics & Astronomy, University of Leicester, Leicester LE1 7RH

Accepted 2011 January 10. Received 2010 December 28; in original form 2010 January 17

ABSTRACT

It has long been recognized that the main obstacle to the accretion of gas on to supermassive black holes (SMBHs) is a large specific angular momentum. It is feared that the gas settles in a large-scale disc, and that accretion would then proceed too inefficiently to explain the masses of the observed SMBHs.

Here we point out that, while the mean angular momentum in the bulge is very likely to be large, the deviations from the mean can also be significant. Indeed, cosmological simulations...
Thank you