Heating and Cooling in Clusters & Galaxies

- review of the white & rees model
- hydrodynamical simulations
- hot and cold flows
- multi-phase cooling
- feedback: photoionization, SN, AGN

Key:
dark matter
hot gas
cold gas
t₁
t₄

Shock Waves

- Basic idea of shocks:
  - occurs in supersonic motion of a fluid:
  - sound waves traveling against the flow cannot travel and pressure builds, creating a high pressure shock wave
  - a sharp increase in density, pressure, temperature and speed at the shock

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White & Rees, White & Frenk 1991

- when $R_{\text{cool}} < R_{\text{vir}}$, accretion from a quasi-hydrostatic gas halo regulated by the cooling rate
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Shock wave
Expansion waves

Time
Pressure
Shocks in Cosmology

- Virial Shocks
- Shocks in merging clusters
- Shocks in moderately dense filaments -- heat the IGM
- Shocks in the ISM and ICM from eg. SN or other energy sources

Virial Shock Heating

- as halos collapse, the dark matter undergoes violent relaxation
- within the virial radius, dm shells cross and the pressure of the gas increases, prevents shell crossing of the gas
- gas is infalling at greater than the sound speed. pressure makes this velocity vanish at the center.
- because it’s supersonic, info about the boundary condition can’t propagate outwards, and a shock is created.
- as the shock propagates outwards, gas that crosses the shock is heated. this increases the sound speed and makes the interior flow subsonic.
- net result is transfer of KE of the collapse into thermal energy of the gas
- in order to persist, the gas internal to the shock has to have pressure.

Clusters are surrounded and filled with a complex pattern of shock waves

SHOCKS OF DIFFERENT MACH NUMBER AROUND A CLUSTER

Cooling Basics

- In the White & Rees model (standard semi-analytic)
  - cooling rate defines cooling time
  - radius where cooling time = \( t_{\text{universe}} \) defines the 'cooling radius' within which gas cools
basics of hydro simulations

The baryons in the universe can be modelled as an ideal gas

**Basic Hydrodynamical Equations**

**Euler equation:**
\[
\frac{dv}{dt} = -\frac{\nabla P}{\rho} - \nabla \Phi
\]

**Continuity equation:**
\[
\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0
\]

**First law of thermodynamics:**
\[
\frac{du}{dt} = -\frac{P}{\rho} \nabla \cdot \mathbf{v} - \frac{\Lambda(u, \rho)}{\rho}
\]

**Equation of state of ideal monoatomic gas:**
\[
P = (\gamma - 1)\rho u, \quad \gamma = 5/3
\]

What is smoothed particle hydrodynamics?

**Different Methods to Discretize a Fluid**

**Eulerian**
- Discretize space
- Representation on a mesh (volume elements)
- Principle advantage: high accuracy (shock capturing), low numerical viscosity

**Lagrangian**
- Discretize mass
- Representation by fluid elements (particles)
- Principle advantage: resolutions adjusts automatically to the flow

Eulerian

Lagrangian

There are principal differences between SPH and Eulerian schemes

**Fundamental Difference Between SPH and Mesh-Hydrodynamics**

**Eulerian**
- Not Galilean invariant
- Sharp shocks and contact discontinuities
  - (but Lagrangian schemes resolve fluid discontinuities in one cell)
- Mixing happens implicitly at the cell level
  - (can provide closure for turbulence, but may also be a source of spurious mixing entropy from advection errors)
- Gravity of the gas naturally treated with the same accuracy as the dark matter
  - Requires artificial viscosity (lowers Reynolds numbers heavily)

**Lagrangian**
- Galilean invariant
- Shocks broadened over roughly 2-3 smoothing lengths
  - (post-shock properties are correct through)
- Mixing entirely suppressed at the particle level
  - (no apokausis entropy production, but fluid instabilities may be suppressed)
- Self-gravity of the gas needs to be done on a mesh
  - (but dark matter must still be represented by particles)
  - Low numerical viscosity
key observations

- The Galaxy Luminosity Function
- Bimodality in galaxy colors
- Early formation of galaxies in clusters
- Properties of gas in clusters

galaxy formation is not equally efficient at all masses:
need for feedback and/or non-standard cooling
Only ~8% of baryons are in stars (Fukagita, Hogan and Peeples 1998, Bell et. al. 2003, Fukagita et al. 2004)

Halo Baryons: \( f_M \)

Bell et al. 03

A Maller

Simulations with no or weak feedback tend to overpredict the cosmic star formation history substantially

Feedback can cure the overcooling problem and regulate star formation

But: K-band results suggest values for \( \Delta_{\text{late}} / \Delta_{\text{early}} \) below 10%

V Springel

The shapes of the CDM halo mass function and the K-band luminosity function are very different

Feedback can cure the overcooling problem and regulate star formation

Feedback is needed to shape the luminosity function of galaxies

Benson et al. (2003)
Feedback appears required to pollute low density gas in hierarchical models of galaxy formation in CDM universes

**KEY AREAS WHERE FEEDBACK IS ESSENTIAL**

- Feedback can cure the overcooling problem and regulate star formation
- Feedback is needed to shape the luminosity function of galaxies
- Feedback is required to explain intergalactic metals
- Feedback may solve the angular momentum problem

V Springel

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Abadi, Navarro, Steinmetz & Eke (2003)

V Springel
SN Feedback

\[ \Delta M_{\text{reheat}} = \varepsilon \left( \frac{4}{3} \right) \left( \eta_{SN} E_{SN}/V_{\text{vir}}^2 \right) \Delta M_{\text{star}} \]

in presence of UV ionizing background, halos with virial temp < background radiation field are unable to accrete gas (\(\sigma < 30-50\) km/s)

- gas can be “boiled out” of halos (\(\sigma < 20\) km/s)
- cooling function modified (cooling suppressed at low T)
- naturally leads to suppression of low mass galaxies.

Photoionization squelching
Cold Flows

**Growth of a Massive Galaxy**

- Shock-heated gas
- “disc”

Spherical hydro simulation  Birnboim & Dekel 03

**A Less Massive Galaxy**

- Cold infall
- Shocked
- “disc”

Spherical hydro simulation  Birnboim & Dekel 03
fraction of cold vs hot accretion

Keres et al

Mass Distribution of Halo Gas

Analysis of Eulerian hydro simulations by Birnboim, Zinger, Dekel, Keres et al.

Keres et al. 2005
Multi-phase cooling
Cooling and Fragmentation in Astrophysical Plasmas

- A cooling plasma is hydrodynamically unstable (Field 1965)
- Higher density regions will cool faster, becoming denser and therefore cooling faster. Low density regions won’t cool as quickly, will expand into the space left by the high density regions, thus decreasing their density and the rate that they cool.
- One ends up with a two phase medium of low density hot gas and warm clouds.

• 2/3 of the baryons cool forming a Milky Way mass of $12 \times 10^{10}$, twice what is observed.
• Supernova feedback is invoked to blowout half of the Milky Ways while not destroying the thin disk.
Cloud-Cloud collisions

Clouds will move around in the halo until they collide or lose energy from ram pressure. Only then will they merge with the galaxy.

\[ M_h \propto \rho_c R_c^3 \]

- Multi-phase cooling seems to predict this cutoff naturally.

Density in a pure disk galaxy

High Velocity Clouds: HI clouds detected around our galaxy not associated with the disk.
When gas cools we expect a two phase medium to arise.

To survive warm clouds must have masses of $10^5 - 10^8$ solar masses.

To get the observed Milky Way mass clouds must have masses of $10^6 - 10^8$

To match the observed properties of high velocity clouds requires cloud masses of $3-7 \times 10^6$ solar masses.

A similar range of cloud masses is needed to produce quasar absorption systems.

Irrespective of the cloud mass, the hot low density core sets an upper limit on the amount of mass that can cool of $2 \times 10^{11}$ solar masses explaining the exponential cutoff in the Luminosity function.

**M_{BH}-\sigma relation**

Haehnelt & Kauffmann 2000

**QSO luminosity function**

Haehnelt & Kauffmann 2000

AGN Feedback
The rise and fall of quasar activity

The co-evolution of galaxies, quasars, and SMBH

- basic premise:
  - major mergers feed gas to central BH and trigger AGN activity → built-in connection between BH and spheroid formation
  - when galaxies merge, their central BH merge as well (conserving mass)

energy injection from the AGN

Fig. 1. Mass-weighted temperature maps of a $10^{13} h^{-1} M_\odot$ isolated halo, subject to AGN bubble heating. The velocity field of the gas is over-plotted with white arrows.

The AGN radio mode

In the radio mode, gas can hot gas accretes onto the central supermassive black hole. Subsequent accretion comes from the surrounding hot halo, where we capture the mean behaviour with an empirical equation:

$$m_{\text{BH,R}} = \kappa_{\text{AGN}} \left( \frac{M_{\text{BH}}}{10^9 M_\odot} \right) \left( \frac{f_{\text{out}}}{0.1} \right) \left( \frac{V_{\text{vir}}}{200 \text{ km s}^{-1}} \right)^2$$

The AGN quasar mode

In the quasi-steady-state, active black holes grow through merging events where black holes coalesce and cold disk gas is driven onto the central black hole.

$$\Delta m_{\text{BH,Q}} = \frac{f_{\text{BH}} m_{\text{cold}}}{1 + (280 \text{ km s}^{-1}/V_{\text{vir}})^2}$$

D Croton
Luminosity Functions

The K and bJ-band luminosity functions with and without AGN.

Galaxy Colours and Ages

B-V colour bi-modality and mean stellar age.

Why Does Such Heating Work?

Unlike other heating mechanisms (e.g., super-winds, starbursts, ...), AGN heating suppresses star formation without itself requiring star formation to efficiently operate.

Unlike “event” mechanisms (e.g., merger-driven quasar winds), whatever quenches star formation needs to be an ongoing process (local massive ellipticals are not quasars!).

An AGN-like low energy heating source, fed from the hot x-ray halo, is an energetically feasible candidate.

Shock Heating Triggers AGN Feedback

\[ M > M_{\text{shock}} \]

More than enough energy is available in AGNs.

Hot gas is vulnerable to AGN feedback, while cold streams are shielded.

*Shock heating is the trigger for AGN feedback in massive halos.
• joint formation of SMBH and spheroids leads naturally to scaling relations BUT strong differential feedback needed

• also needed to make big BH at z~6 without overproducing BH mass density

• rise and fall of quasar activity (maybe) tied to same physics as star formation rate in galaxies (merger rate/gas supply)

While halos grow by mergers and accretion

\( M < M_{\text{crit}}: \text{The Blue Sequence} \)
- cold gas supply \( \Rightarrow \) disk growth & star formation
- SN-fdbk regulates star formation \( \Rightarrow \) long duration bursts \( \Rightarrow \) very blue
- mergers & bar instability \( \Rightarrow \) bulges

\( M > M_{\text{crit}}: \text{The Red Sequence} \)
- shock-heated gas + AGN fdbk \( \Rightarrow \) no new gas supply
- + gas exhausted + AGNs especially in bulges
- \( \Rightarrow \) no disk growth, star formation shuts off
- passive stellar evolution \( \Rightarrow \) red & dead
- further growth of spheroids by gas-poor mergers

Physics in GADGET-II for simulations of galaxy formation
- Radiative cooling, UV background (homogeneous)
- Subresolution multiphase model for the ISM: Star formation and feedback
- Phenomenological model for galactic winds
- Detailed chemical enrichment
- Thermal conduction
- Magneto-hydrodynamics
- Non-thermal relativistic component (cosmic rays)
- Growth of supermassive black holes and AGN feedback
- Bubble heating and feedback by AGN
- Shock detection
- Physical viscosity via Navier-Stokes equation