COOLING AND HEATING PROCESSES IN COSMOLOGICAL SIMULATIONS

Primary reference: Katz, Weinberg, & Hernquist 1996, ApJ Supp, 105, 19 (KWH)

Motivation: Dissipation and Galaxy Formation

- Merging of dark matter halos in N-body simulations: don't get clusters of halos
- Gas dynamics without cooling: gas shock heats, stays pressure supported in dark matter halos
- Gas dynamics with cooling: densest gas cools, loses pressure support, contracts to form dense lumps with sizes characteristic of observed galaxies. These lumps survive as distinct entities when dark halos merge

Gas Dynamics Equations

SPH formulation

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot (\rho \mathbf{v}) \quad \text{mass conservation}$$

$$\frac{\partial \mathbf{v}}{\partial t} = -\vec{\nabla}\Phi - \frac{\vec{\nabla} P}{\rho} + \mathbf{a}_{\mathrm{visc}} \quad \text{momentum conservation}$$

$$\frac{\partial \epsilon}{\partial t} = -\frac{P}{\rho}\vec{\nabla} \cdot \mathbf{v} + \frac{Q_{\mathrm{visc}}}{\rho} + \frac{Q - \Lambda(\rho, T)}{\rho} \quad \text{energy conservation}$$

$$P = (\gamma - 1)\rho\epsilon \quad \text{equation of state}$$

- Heating: adiabatic compression, shocks, photoionization
- Thermal energy equation, eventually affects equation of motion through pressure

Cooling Curve for Primordial Composition Gas

(See KWH, figure 1)

- $\Lambda \propto n_{\mathrm{H}}^2$ (two-body processes)
- $\Lambda / n_{\mathrm{H}}^2 \propto T^{1/2}$ for $T > 10^6$K (dominant process, free-free emission)
- Bumps at $T \sim 10^{4.2}$K (H line excitation), $T \sim 10^{4.8}$K (He^+ line excitation)
- Cutoff at $T \sim 10^4$K (gas too cool to produce excitation)
- Ionic abundances computed assuming collisional equilibrium $\Longrightarrow$ balance between creation and destruction rates, only collisional ionization (no photoionization)
- The general approach:
  (a) Compute ionic abundances by direct integration (beware, timescales can be short, so equations are stiff) or by solving for equilibrium (see KWH, §3.1).
  (b) Add up cooling rates for all processes given temperature, density, and ionic abundances.

Complications

- Compton cooling off CMB. Important for ionized gas at $z \gtrsim 7$.
- Molecular hydrogen cooling. Needed to get from $T \sim 10^4$K to $T \sim 100$K (necessary for star formation). Requires very high densities, so only relevant for calculations with high resolution.
- Metal-line cooling. Crucial in ISM. Less important (probably) for galaxy formation because metallicity of pre-galactic gas is low.
- Photoionization. Eliminates H/He$^+$ "bumps" in cooling curve at low density. Important effect on formation of dwarf galaxies (circular velocities $v_c \lesssim 50\,\mathrm{km\,s^{-1}}$), but not of large galaxies. Photoionization crucial for modeling Lyman-alpha forest.

Some other references

Molecular cooling in cosmological simulations
Abel, Anninos, Zhang, & Norman 1997, New Astronomy, 2, 181

Photoionization and galaxy formation
Quinn, Katz, & Efstathiou 1996, MNRAS, 278, L49
Thoul & Weinberg 1996, ApJ, 465, 608
Weinberg, Hernquist, & Katz 1997, ApJ, 477, 8