The physics of AGN feedback in clusters of galaxies

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with help by

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Perseus

green: 330 MHz
yellow: 1.4 GHz
blue: Chandra (227 ks)

total energy = $10^{61}$ erg

bubbles stay intact for long times
Evidence for turbulence in clusters

• metal profiles in clusters (e.g. Simionescu et al. 2008, Rebusco et al. 2006)
• lack of resonant scattering in 6.7 keV Fe line in Perseus (Churazov et al. 2004)
• Faraday rotation maps (e.g. Enßlin & Vogt 2003)
• non-thermal emission in clusters (e.g. Brunetti & Lazarian 2007)
Faraday rotation

magnetized cluster gas

polarized radio galaxy

probed volume

Faraday rotation map

\( \lambda_B \)

\( \lambda_{RM} \)
Faraday rotation

Maximum likelihood power spectrum estimate using 3-d window, assuming statistical isotropy, $\text{div } B = 0$.

Hydro turbulence induced by buoyantly raising radio bubbles has the right strength & length-scale to drive observed magnetic turbulence (Enßlin & Vogt 2006)
Simionescu, Böhringer, Brüggen, Finoguenov (2006)
Metals in Perseus

Rebusco et al., MNRAS 359, 1041 (2005)
Cooling time

Perseus cluster

Other clusters
Voigt & Fabian 2003
The ICM may be turbulent

Rayleigh-Taylor unstable bubbles induce turbulence

AGN-blown bubbles stay intact for long times

Rayleigh-Taylor instabilities cannot be simulated for Re > 10000

Main Question:
How much turbulence do bubbles produce in the ICM and what does this turbulence do to the bubbles?
Rayleigh Taylor Instability

Dense Fluid

Light Fluid
Rayleigh Taylor Instability

\[ h_b = \alpha_b A_o g t^2 \]

\[ A_i = \frac{\bar{\rho}_+ - \bar{\rho}_-}{\bar{\rho}_+ + \bar{\rho}_-} \]
Dimonte & Tipton 2006 Turbulence Model

based on buoyancy-drag models for RT and RM instabilities: self-similar, conserves energy, preserves Galilean invariance, works with shocks

\[
\begin{align*}
\frac{\partial \bar{\rho}K}{\partial t} + \frac{\partial \bar{\rho}K \bar{u}_j}{\partial x_j} &= \frac{\partial}{\partial x_j} \left( \frac{\mu_t}{N_K} \frac{\partial K}{\partial x_j} \right) - R_{i,j} \frac{\partial \bar{u}_i}{\partial x_j} + S_K \\
\frac{\partial \bar{\rho}L}{\partial t} + \frac{\partial \bar{\rho}L \bar{u}_j}{\partial x_j} &= \frac{\partial}{\partial x_j} \left( \frac{\mu_t}{N_L} \frac{\partial L}{\partial x_j} \right) + \bar{\rho}V + C_C \bar{\rho}L \frac{\partial \bar{u}_i}{\partial x_i},
\end{align*}
\]

turb. diffusion  work associated with turbulent stress  source term with RM and RT contributions

turb. diffusion  growth of eddies through turb. motion  growth of eddies through motion in mean flow

\[
S_K = \bar{\rho}V \left[ C_B A_i g_i - C_D \frac{V^2}{2} \right], \quad \mu_T = C_\mu \bar{\rho}L V, \quad V \equiv \sqrt{2K}
\]

buoyancy  drag  turb. viscosity  turb. velocity
Modified fluid equations

leading order in expansion around mean velocity: mean quantities are modified by presence of:

1. Reynolds stress $R$
2. Turbulent viscosity, $\mu$
3. Source term $S_K$

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} - \frac{\partial R_{i,j}}{\partial x_j}
\]

\[
\frac{\partial \rho E}{\partial t} + \frac{\partial \rho E u_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\mu_t}{N_E} \frac{\partial E}{\partial x_j} \right) - \frac{\partial P u_j}{\partial x_j} - S_K
\]
Rayleigh-Taylor Shock Tube Test from DT06

solid: simulation
dashed: analytic

\[ L(x, t) = L(t, 0)[1 - x^2/h(t)^2]^{1/2} \]
\[ K(x, t) = K(t, 0)[1 - x^2/h(t)^2] \]
\[ h(t) = \alpha A(0)t^2 \]
\[ L(t, 0) = h(t)/2 \]
\[ K(t, 0) = (dh/dt)^2/2 \]

K, L and \( \mu \) increase as \( t^2 \) -> rapid mixing between materials
Simulation setup

- numerical implementation in FLASH3.0 framework
- Equations for K and L are evolved explicitly (with addl. timestep constraint)
- momentum and energy equation modified by source term, Reynolds tensor and turbulent viscosity
- initially hydrostatic cluster, static gravity
- 5 levels of refinement (3-6), 1024^3 eff. res., (650 kpc)^3 box
- bubbles are produced by
  (a) evacuation in pressure equilibrium
  (b) injection of energy into spherical regions (Sedov-type), r = 10 kpc
- metal injection proportional to light distribution
- metal fraction in each cell represented by mass scalar
- radiative cooling by thermal bremsstrahlung
metals

X-ray emission

50 Myr
100 Myr
150 Myr
200 Myr
radialES

red: subgrid
blue: w/o subgrid

1-2% of E_buoy
T increase not due to turbulent dissipation but mixing.

- **Red**: with subgrid
- **Blue**: w/o subgrid
- **Green**: no bubbles

**Figure**: Periodic evacuated bubble run

- **Y-axis**: $\log_{10}[S/\text{keV cm}^2]$ vs. $\log_{10} [T/\text{keV}]$
- **X-axis**: radius/kpc

**Legend**:
- 150 Myrs
- 300 Myrs
- 450 Myrs
In pure hydro run, bubbles fragment after single pressure scale height.

Dominant unstable modes are set by grid resolution.

Subgrid models captures growth of modes that the grid cannot resolve.

It smears out the interface between bubble and ambient medium and keeps the bubbles intact.

Metal transport is enhanced.
astro-ph 0806.3268
Dependence on resolution

$$\lambda_{\text{max}} = 4\pi (\nu^2 A/g)^{1/3}$$

Re $\sim 2000 - 5000$

$$\nu \sim d\nu/\text{Re} \sim 3 \text{ km s}^{-1}\text{kpc}$$

$$\lambda_{\text{max}} \sim 2 \text{kpc}$$
periodic evacuated bubble run

w/o subgrid with subgrid corresponding unsharp-masked X-ray images

150 Myr

300 Myr

450 Myr
periodic Sedov bubble run

w/o subgrid  with subgrid  corresponding unsharp-masked X-ray images

100 Myr

200 Myr

300 Myr

(periodic mean shock)
red: Sedov
blue: evacuated bub

1-2% of $E_{\text{exp}} + E_{\text{buoy}}$
1-2% of $E_{\text{buoy}}$
No Turbulence

Turbulence

Shocks

Perseus A
Conclusions

• We tried a K-L subgrid model to study the RT and RM driven turbulence in galaxy clusters.

• RT and RM instabilities that drive the evolution of bubbles result in motions on many scales that are far below the resolution limit of current simulations. The superposition of unstable modes smears out the interface between bubbles and ambient medium and prevents break-up of bubbles. This mixing explains the appearance of X-ray cavities. Subgrid models are needed to capture this physics.

• Subgrid turbulence enhances metal transport in clusters; typical turbulent diffusivity: 500 km/s kpc - in line with observations of metal profiles in Perseus.

• Turbulent energy is about 1% of total energy in bubbles available to heat the cluster. Subgrid turbulence plays no role in heating cool cores.

• Turbulent motions can be probed with Con-X.

• In simulations where RT and RM instabilities occur, proper treatment of subgrid physics can be essential!