Turbulent Heating in the X-ray Brightest Galaxy Clusters


SnowCluster, Snowbird, Utah, March 15-20, 2015
Turbulent dissipation in AGN feedback

energy release => bubbles => ? => heating

Possible channeling mechanisms:
shocks, sound waves (Randall et al. 11; Fabian et al. 06)
turbulent dissipation (Churazov et al. 02; Fukita et al. 04; Banerjee et al. 14)
turbulent mixing (Kim & Narayan 03)
cosmic rays (Chandran & Dennis 06; Pfrommer et al. 13)
radiative heating (Ciotti & Ostriker 01; Nulsen & Fabian 00)
etc.
Definitions and assumptions

Kinetic energy and Magnetic energy

stratified turbulence $k_{\perp}^{-5/3}$

isotropic turbulence $k^{-5/3}$

unmagnetized and magnetized

assumptions:
- no magnetic fields
- no plasma effects
Turbulent dissipation in AGN feedback

\[ Q_{\text{turb}} = K_0 \rho \frac{V^3}{l} \]

- Kolmogorov constant
- Velocity amplitude on scale \( l \)
- Gas mass density

Kolmogorov 41
Sreenivasan et al. 95
Kaneda et al. 03
Dennis & Chandran 05
Is there any way to probe gas dynamics using currently-available data?

\[ \delta \rho \rightarrow V? \]
How do density perturbations scale with the velocity field?

homogeneous box

\[ \delta \rho \propto M^2 \]
from Bernoulli's equation (solenoidal motions)

stratified atmosphere
g-modes in stratified atmosphere

stratification in clusters:
gradient of $S, \rho$

small and slow perturbations $\Rightarrow$ g-modes (internal or gravity waves)

High-entropy gas

$N_{BV}$

Low-entropy gas

Surface gravity waves
g-modes in stratified atmosphere

Dispersion relation:

$$\omega^2 = N^2 \frac{k^2}{k^2}$$

Brunt-Väisälä frequency:

$$N = \sqrt{\frac{g}{\gamma H_s}}$$

Entropy scale height:

$$H_s = \left(\frac{d \ln S}{dr}\right)^{-1}$$

Wavenumber: $$k^2 = k^2_\perp + k^2_r$$

g-modes are confined inside the cluster core => interact => non-linear => turbulent motions

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Balbus & Soker, 1990
g-modes in stratified atmosphere

\[ \omega^2 = N^2 \frac{k_\perp^2}{k^2} \]

if \( \omega << N \) (stratification is important) \( \Rightarrow \)

\[ k_\perp << k_r \]

in "\( \perp \)" direction

in "\( r \)" direction

"pancake" turbulence

on large scales \( V \) is dominated by \( V_\perp \)

Waite & Bartello 2006
Buoyancy-dominated regime of motions

stir the gas slowly with \( \omega << N_{BV} \)

Turbulent eddy at injection scale \( L \):

\[ \Delta r \approx \omega / N_{BV} \]

\[ V_{\perp} = L \omega \sim V \]

\[ V = N_{BV} \Delta r \]

gravity provides \( V - \Delta r \) relation
Gas displacement and density contrast

\begin{align*}
P &= (S_b + \delta S) \rho^\gamma \\
P &= S_b \rho_b^\gamma \\
\end{align*}

Density contrast after (slow) gas displacement:

\[
\frac{\delta \rho}{\rho} = \frac{1}{\gamma} \frac{\delta S}{S} \approx \frac{1}{\gamma} \frac{\Delta r}{H}
\]

entropy gradient gives \(\delta \rho - \Delta r\) relation

density contrast after (slow) gas displacement:

\[
\varepsilon \approx 1
\]

gas in pressure equilibrium \(P_b = P\)

slow displacement \(S_b = \text{const}\)

entropy scale height
Buoyancy-dominated regime of motions

entropy gradient:
\[
\frac{\delta \rho}{\rho} = \frac{1}{\gamma} \frac{\Delta r}{H_s}
\]

gravity:
\[
V = N_{BV} \Delta r
\]
\[
N_{BV} = \frac{c_s}{\gamma \sqrt{H_s H_p}}
\]
\[
\frac{\delta \rho}{\rho} = \eta \frac{V}{c_s}
\]
\[
\eta = \sqrt{\frac{H_p}{H_s}} \sim 1
\]
valid on large, buoyancy-dominated scales

the system adjusts so that \( \eta \sim 1 \)
Turbulent small-scale regime: $t_{\text{eddy}} << t_N$

Obukhov-Corrsin approach:
the spectrum of the passive scalar follows the spectrum of the velocity field in the inertial range
Obukhov 1949; Corrsin 1951

\[
\frac{\delta \rho_k}{\rho} = \eta \frac{V_k}{c_s}
\]

$\eta \sim 1$ is set on large, buoyancy-dominated scales.
Verifying the coefficient $\eta$

AMR cosmological simulations, NR runs, relaxed clusters

Kravtsov et al. 99;03; Nagai et al. 07a; Nelson et al. 14

$\eta = 1 \pm 0.3$

Zhuravleva et al. 2014a

hydro simulations: $\eta \sim 1$ w/o conduction

Gaspari et al. 2014
Nature of fluctuations in Perseus

1) sound waves  (Fabian et al. 03; 06; Sanders et al. 07)
2) stratified turbulence  (Zhuravleva et al. 14; 15)
Nature of fluctuations in Perseus: stratified turbulence?

\[ \Delta r \sim HV/c_s \]

cross-spectra analysis of SB fluctuations in different energy bands: isobaric fluctuations (gas sloshing, turbulence, g-modes)
Amplitude of density fluctuations in Perseus

\[ I_X \propto \int n_e^2 \epsilon(T) \, dl \propto \int n_e^2 \, dl \]
Amplitude of density fluctuations in Perseus

\[ A_{3D}^2(k) = 4\pi P_{3D}(k) k^3 \]

Units are the same of the variable in real space

outside central 30 kpc: \[ \frac{\delta \rho_k}{\rho} \sim 7 - 15\% \] on scales 6-30 kpc
Velocity Power Spectrum in Perseus

\[ V_k = c_s \frac{\delta \rho}{\rho} \]

- V higher towards the center \( \rightarrow \) power injection from the center
- larger V on smaller k \( \rightarrow \) consistent with cascade turbulence
- 70 km/s < \( V_{1,k} \) < 200 km/s on scales 6-30 kpc (within central 200 kpc)

Turbulent dissipation in AGN feedback

\[ Q_{\text{turb}} = K_0 \rho \frac{V_l^3}{l} \]

Kolmogorov constant

velocity amplitude on scale \( l \)

gas mass density

Kolmogorov 41
Sreenivasan et al. 95
Kaneda et al. 03
Dennis & Chandran 05

we measure \( V_l \) and each scale \( l \) => can obtain \( Q_{\text{turb}} \)
Turbulent dissipation in AGN feedback

cooling rate:
\[ C = n_e n_i \Lambda_n(T) \]

heating rate:
\[ H(k) = C_H \rho V_{1,k}^3 k \]

locally: cooling \(\sim\) heating

AGN \(\rightarrow\) Bubbles \(\rightarrow\) Turbulent dissipation \(\rightarrow\) Heat

Zhuravleva et al. 2014b
If we assume Cooling~Heating, then:

\[ M_k \approx 0.15 \left( \frac{n_e}{10^{-2} \text{ cm}^{-3}} \right)^{1/3} \left( \frac{c_s}{1000 \text{ km/s}} \right)^{-1} \left( \frac{l}{10 \text{ kpc}} \right)^{1/3} \]

Dissipation of turbulence with M~0.15 is sufficient to balance cooling of the gas in cores
What happens outside cool cores?

our expectations:

t \sim \text{cooling} \sim \text{heating}

\begin{align*}
t_{\text{cool}} & \quad \text{red line} \\
t_{\text{Hubble}} & \quad \text{horizontal line} \\
t_{\text{heat}} & \quad \text{blue curve}
\end{align*}
What happens outside cool cores?

XMM-Newton, Perseus

Dissipation of gas motions on timescales ~ cluster age

Work in progress
Uncertainties (incomplete list)

1. Bias in the normalization of the amplitude of density fluctuations from the $\Delta$-variance method: $\sim 1.3$ (Perseus) and 1.2 (Virgo);
2. Division of cluster into “perturbed” and “unperturbed” components: small-scale power is robust;
3. Conversion between 2D to 3D power spectrum: $< 20%$;
4. Accuracy of the Poisson noise subtraction, PSF correction, unresolved point sources correction - robust regions;
5. Stochasticity of density fluctuations - broad annuli;
6. Weighting scheme used to calculate the amplitude of fluctuations: $< 20%$;
7. We cannot prove that we see turbulence;
8. $\eta$ scatter is $\sim 30\%$, not sure that it is the same in the range of scales - Ozmidov scale is within the range of scales we are probing;

etc.

- final uncertainty in the heating rate is $\sim$ a factor of 3
- Astro-H is needed to calibrate density/velocity relation
Summary

\[ \frac{\delta \rho_k}{\rho} = \eta \frac{V_{1,k}}{c_s} \]

• relaxed clusters
• subsonic motions
• simplest approach

V measurements on different scales:
• Perseus: 70 km/s < V_{1,k} < 200 km/s on 6 - 30 kpc (within ~ 200 kpc)
• Virgo: 40 km/s < V_{1,k} < 90 km/s on 2 - 10 kpc (within ~ 40 kpc)

AGN-feedback:
• turbulence dissipation is sufficient to offset cooling locally at each r
• AGN —> Bubbles —> Turbulent dissipation —> Heat

Nature of fluctuations in Perseus:
dominated by isobaric fluctuations (gas turbulence, sloshing, g-modes)

Astro-H (end 2015), Athena (2028), Smart-X (?):
• verification of the linear relation, importance of microphysics
• nature of fluctuations
Velocity Power Spectrum in Virgo

40 km/s < $V_{1,k}$ < 90 km/s on scales 2 - 10 kpc

Zhuravleva et al. 2014b, Arevalo et al. in prep.
Known unknowns in ICM (incomplete list)

- velocity field (turbulence, gas sloshing)
- transport processes (viscosity, diffusion, convection, conduction)
- heating of ICM
- cosmology: non-thermal pressure
- particle acceleration
- amplification of mag. fields
- origin of radio halos

crucially important for gastrophysics, plasma physics, cosmology
$P_{2D}$ of SB $\rightarrow$ $P_{3D}$ of density fluctuations

$A_{2D}^2 = 2\pi P_{2D} k^2$

$A_{3D}^2 = 4\pi P_{3D} k^3$ $\Rightarrow$ $P_{2D} \propto P_{3D} \frac{1}{L}$

$A_{3D} = \delta \rho / \rho_{10}$

Churazov et al. 12; Zhuravleva et al. 12
Measured velocities (so far):

Perseus: $70 \text{ km/s} < V_{1,k} < 200 \text{ km/s}$ on scales $6-30 \text{ kpc}$
M87: $40 \text{ km/s} < V_{1,k} < 90 \text{ km/s}$ on scales $2 - 10 \text{ kpc}$

NGC4636: $V<100 \text{ km/s}$ (RS) (Werner, IZ et al. 2009)
NGC 5044: $300 \text{ (RS)} < V < 950 \text{ (width)} \text{ km/s}$ (de Plaa, IZ et al. 2012)
NGC 5813: $100 \text{ (RS)} < V < 670 \text{ (width)} \text{ km/s}$ (de Plaa, IZ et al. 2012)
A1835: $V< 274 \text{ km/s}$ (width) (Sanders et al. 09)
62 cores of clusters: $V < 700/500 \text{ km/s}$ (width) (Sanders et al. 11)
44 cores of clusters: $V< 500 \text{ km/s}$ (width) (Pinto et al. 2015)
Nature of fluctuations in Perseus

Adiabatic fluctuations
(sound waves, shocks):
\[ \rho \uparrow, \ T \uparrow \ \Rightarrow \ P \uparrow \]

Isobaric fluctuations
(gas sloshing, turbulence, g-modes):
\[ \rho \uparrow, \ T \downarrow \ \Rightarrow \ P \sim \text{const} \]
Nature of fluctuations in Perseus

\[ F \propto n^2 \epsilon(T) \]

\( \epsilon(T) \), 0.5–3.5 keV

independent of \( T \)

\( \epsilon(T) \), 3.5–7.5 keV

increases with \( T \)

soft band: density

hard band: \( T \)-dependent

need to compare the PS of SB fluctuations in both bands

Work in progress
Do we see Kolmogorov slope of the spectrum?

\[ E_{\perp}(k_{\perp}) \quad E_{\perp}(k_{r}) \]

\[ k_{\perp}^{-5/3} \quad k_{r}^{-5/3} \]

Ozmidov scale:

\[ k_{O} = N^{-3/2} \varepsilon^{1/2} \]

Ozmidov 1992
Do we probe turbulence within the inertial range?

We do not plot the one-component velocity amplitude calculated for data from such image. Notice, that the velocity amplitude decreases with distance from the center. Colored shaded regions are due to turbulence only. For example, there are new regions: range of scales, on which we calculate the PS of density fluctuations of clusters.

Less general definitions are also used in the literature. For example, Pedlar et al. 1990; Boehringer et al. 1993; Churazov et al. 2007), which arises naturally is cluster atmospheres, stratified turbulence (Zhuravleva et al. 2014a; Brethouwer et al. 2013; Brethouwer et al. 2014, 2015; Fabian et al. 2000, 2003). An alternative interpretation is that sound waves (Fabian et al. 2006; Sternberg & Soker 2007) might also contribute to the observed density fluctuations in the central region of the Perseus Cluster. Unsharp masking of the Perseus Cluster in the central 1 arcmin annulus, this factor is 3 depending on scale in the measured PS.

Change the measured velocity amplitude. However the contribution of the bubbles to the signal can be easily seen if we repeat the analysis excluding the know bubbles from the image of Perseus. The velocity amplitude decreases with distance from the center.

By gas clumping we will mean any deviations of the gas density and temperature isosurfaces from the equipotential surfaces. This definition includes both: large-scale inhomogeneities (e.g. induced by gas sloshing, perturbations of potential) and small-scale clumpiness (e.g., caused by gas turbulence, motions of galaxies and subhalos etc). That is to say, we do not probe turbulence within the inertial range of the dissipation scale (for unmagnetized plasma) < scales we are probing.
Power spectrum $V \sim \rho$

$P(k)$

dominated by buoyancy

buoyancy not important

$\frac{\delta \rho_k}{\rho} \eta \sim 1$

Zhuravleva, Churazov, Schekochihin et al. 2014a
**Gas dynamics in simulations**

**ICM turbulence within $r_{500}$:**
- driven by mergers and central AGN
- typical $V \sim$ few 100s km/s, sound speed $\sim 1000$-$1300$ km/s
- mostly subsonic (in relaxed clusters), $M<0.5$
- nearly incompressible
- $\sim$Kolmogorov slope $-5/3$ of $E(k)$
- up to 30 % non-thermal pressure contribution
Amplitude of density fluctuations in Perseus

PS calculations using modified Δ-variance method (Arevalo et al. 2012)

Next step: \( P_{2D} \) of SB \( \rightarrow P_{3D} \) of density
Amplitude of density fluctuations in Perseus

statistical approach to probe fluctuations: power spectrum of SB fluctuations
Nature of fluctuations in Perseus

soft band: 0.5-3.5 keV

hard band: 3.5-7.5 keV

Let’s compare the amplitudes of fluctuations by calculating their auto- and cross-spectra

Work in progress
Gas fluctuations in Perseus
(based on Chandra 1.4 Ms observations)

- modest amplitude of density fluctuations: 7-15% on scales 6-30 kpc
- predominantly isobaric fluctuations (preliminary)
- velocity: $70 \text{ km/s} < V_{1,k} < 200 \text{ km/s}$ on scales 6-30 kpc
Turbulent dissipation in AGN feedback

Basic concept of AGN feedback:

radiative cooling of gas $\Rightarrow$ accretion rate onto SMBH $\Rightarrow$ energy release (bubbles) $\Rightarrow$ ? $\Rightarrow$ dissipation of released energy

Churazov et al. 00, Omma & Binney 04, McNamara et al. 07, Fabian et al. 12; Birzan et al. 12

\[ t_{cool} = \frac{3}{2} \frac{nkT}{n^2 \Lambda(T)} \]
What’s next?

Astro-H (Jan 2016)
soft X-ray spectrometer (SXS)

X-ray microcalorimeter array of 6x6 pixels: ~ 5 eV spectral resolution, ~ 1.7’ spatial resolutions, 3’x3’ field of view in the 0.3-12 keV band

T rise upon each incident X-ray photon, achieving ~5eV energy resolution
small-scale motions: $\sigma$  
large-scale motions: $V$

At a given $R$ an interval $L_{\text{eff}} \sim R$ contributes to the line flux (and width)

Observed $\sigma(R) \approx$ structure function ($L_{\text{eff}}$)
Nature of fluctuations in Perseus: sound waves?

rough concentric rings “ripples”

\[ \Delta r \sim \text{time variability of AGN} \]

P jumps, no T jumps

iso thermal sound waves

\[ \text{Fabian et al. 2003, Fabian et al. 2006} \]
Astro-H SXS observations of the Perseus Cluster
Two major problems: “perturbed” and “unperturbed” components

$$I_{mod} = I_{\beta} S_{\sigma} [I_x / I_{\beta}]$$
Two major problems: “perturbed” and “unperturbed” components

\[ k_{\text{supp.}}[1/\arcmin] = 0.8/\sigma[\arcmin] \]

removal of large-scale asymmetry does not change the result amplitude of fluctuations on intermediate scales due to the presence of fluctuations on these scales (not a leakage of power from the larger scales)
The gas clumping factor is usually defined as $\frac{\rho_{\text{gas, clumped}}}{\rho_{\text{gas, uniform}}}$, where $\rho_{\text{gas, clumped}}$ is the mass density of the clumped gas and $\rho_{\text{gas, uniform}}$ is the mass density of the uniform gas. This definition includes both large-scale inhomogeneities (e.g., gas sloshing, perturbations of potential) and small-scale clumpiness (e.g., caused by gas turbulence, motions of galaxies and subhalos etc). That is to say, gas clumping is a scale-dependent characteristic and, therefore, even if bubbles count for discussion.

Characteristic scales in Perseus

Ozmidov scale: $l_0 = N_B V^{-3/2} (Q_{\text{turb}}/\rho)^{1/2}$

Kolmogorov scale: $l_K = V_{\text{kin}}^{3/4} (Q_{\text{turb}}/\rho)^{-1/4}$
Coherence and regression

\[ C = \frac{P_{12}}{\sqrt{P_1 P_2}} \]

Regression:
\[ y = R \cdot x \]
\[ R = \alpha \frac{P_{12}}{P_1} \propto \frac{f_2}{f_1} \]

Regression: isobaric fluctuations (gas sloshing, turbulence, g-modes) are dominating the signal

see talk by E. Churazov