Feedback and the Hot Circumgalactic Medium

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Outline

• An overview of our evolving understanding of gas in a cluster gravitational potential

• Link between hot gas and activity in the central galaxy.

• A model for feedback: Precipitation model inspired by cluster and elliptical galaxy observations by Chandra

• (Why “thermal feedback” doesn’t work)

• Application of the model to lower mass galaxies

• Lynx applications
gas in a dark matter halo
a cartoon
not to scale

- dark-matter dominated (mostly)
- nearly hydrostatic
- $T \sim \frac{M}{R}$

- X-ray luminosity is determined by $\phi_g$ and gas entropy ($K = kT/n_e^{2/3}$)
gas in a dark matter halo
a cartoon
not to scale

"Core"

Not the core

COSMOLOGY-DOMINATED

FEEDBACK-REGULATED

$r \leq 0.15 \, r_{500}$
The Luminosity-Temperature Relation
The Luminosity-Temperature Relation

Self-similar: $L \sim T^{3/2} \Lambda(T)$

- REXCESS Galaxy Clusters ($R_{500}$)
- XXL Galaxy Clusters ($R_{500}$)
- Sun+09 Groups ($R_{500}$)
- Anderson+15 ($R_{500}$)
- Milky Way (100 kpc)
- Milky Way (8 kpc)

- REXCESS Clusters ($R_{500}$)
- XXL Clusters ($R_{500}$)
- Bharadwaj+15 ($R_{500}$)
ACCEPt Entropy Profiles

\[ K = kTn_e^{-2/3} \]

Cavagnolo+2009
233 Chandra clusters
z<0.2
REXCESS (XMM) Entropy Profiles

Pratt+2010

25 representative clusters, z~0.1
gas in a dark matter halo

a cartoon

not to scale

\[ t_{\text{cool}} = \frac{\text{(thermal energy)}}{\text{(luminosity)}} \]

t\(_{\text{cool}}\) increases with gas entropy.

“core” vs. “not core” set by local thermodynamic timescale (\(t_{\text{cool}}\)) and the gravitational timescale (\(t_{\text{ff}}\))
**Multiphase Threshold**

Voit+ 08, Cavagnolo+ 08, Rafferty+ 08

Core Entropy Index = $K_0 = kTn_e^{-2/3}$

equivalent to $t_{\text{cool}} \sim 10^9$ yr
**Multiphase Threshold**

Voit+ 08, Cavagnolo+ 08, Rafferty+ 08

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equivalent to $t_{cool} \sim 10^9 \text{ yr}$

Voit+ 08, Cavagnolo+ 08, Rafferty+ 08
Multiphase Core Gas and \( \min(t_{\text{cool}}/t_{\text{ff}}) \)

Hogan+2017
Abell 2597 (z=0.082)
Brightest Cluster Galaxy
and surrounding environment

Rapidly cooling
X-ray atmosphere

Buoyant X-ray Bubbles

30 kpc (20")

Tremblay+ 2016, Nature
Lyman $\alpha$ from SF-UV clumps in Brightest Cluster Galaxy MACS J1532+30

Donahue+2017

Number of Lyman Break Galaxies (z~3)
Shapley+2 003

Equivalent Width in Angstroms
Lyman $\alpha$ from SF-UV clumps in Brightest Cluster Galaxy MACS J1532+30

Donahue+2017

Number of Lyman Break Galaxies (z~3) Shapley+2003

Equivalent Width in Angstroms
Lyman $\alpha$ from SF-UV clumps in Brightest Cluster Galaxy MACS J1532+30

Number of Lyman Break Galaxies $(z \sim 3)$

Equivalent Width in Angstroms

Donahue+2017

Shapley+2003
Cluster Cooling-Time Profiles

Voit+ 2015, Nature

Note: simple “thermal” AGN feedback does not work.

2.0 < max(kT_x) < 10.0

Can’t Cool

Dynamical Heating

Outburst/Precipitation Cycle

no cooling
isothermal core
conductive balance
precipitating
baseline
Cluster Cooling-Time Profiles

Voit+ 2015, Nature

Note: simple "thermal" AGN feedback does not work.
Cluster Cooling-Time Profiles

Voit+ 2015, Nature

Note: simple “thermal” AGN feedback does not work.
Cluster Cooling-Time Profiles

Voit+ 2015, Nature

Multiphase Gas
- $2-10$ keV, H$\alpha$
- $0.5-2$ keV, far-IR

No Multiphase Gas
- no cooling
- isothermal core
- conductive balance
- precipitation
- baseline

Cluster Cooling-Time Profiles

Voit+ 2015, Nature
The Precipitation Hypothesis

Feedback from the central black hole maintains the CGM in a state marginally unstable to condensation.

Massive Elliptical Galaxies

- stellar mass \( \sim 4 \times 10^{11} \, M_{\text{Sun}} \)
- stellar mass loss \( \sim 1-2 \, M_{\text{Sun}}/\text{yr} \)
- hot gas mass \( \sim 10^9 \, M_{\text{Sun}} \)
- central cooling time \(< 100 \, \text{Myr}\)
Two Kinds of Massive Ellipticals

Werner+ 12, Werner+ 14

Single-

NCG 1399

30 kpc

Multiphas

NGC 5044
**Precipitation Threshold in Ellipticals**

Voit+ 15 (Apr 2015, ApJL), data: Werner+ 12,14

No Extended Multiphase Gas

- X-ray gas profile consistent with galaxy wind

Extended Multiphase Gas

- X-ray gas profile consistent with $t_{cool}/t_{ff} \sim 10$
Precipitation Threshold in Ellipticals

Voit+ 15 (Apr 2015, ApJL), data: Werner+ 12,14

No Extended Multiphase Gas

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Extended Multiphase Gas

- X-ray gas profile consistent with \( t_{\text{cool}}/t_{\text{ff}} \sim 10 \)
Precipitation Threshold in Ellipticals

Voit+ 15 (Apr 2015, ApJL), data: Werner+ 12,14

- No Extended Multiphase Gas
  - X-ray gas profile consistent with galaxy wind

- AGN 100x more powerful than the others!

- Extended Multiphase Gas
  - X-ray gas profile consistent with tcool/tff ~ 10
**Precipitation Threshold in Ellipticals**

Voit+ 15 (Apr 2015, ApJL), data: Werner+ 12,14

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No Extended Multiphase Gas

- X-ray gas profile consistent with galaxy wind

Extended Multiphase Gas

- X-ray gas profile consistent with $t_{\text{cool}}/t_{\text{ff}} \sim 10$

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Lynx science: probe the gas conditions in the centers of ellipticals with and without power radio sources.
Precipitation-Limited Luminosity

Voit, Ma, Greene, Goulding, Pandya, Donahue, Sun 2017, astro-ph, (yesterday), arxiv.org/abs/1708.02189

\[
\frac{t_{\text{cool}}}{t_{\text{ff}}} \gtrsim 10 \quad \text{and} \quad n_e \lesssim \frac{3kT}{10 t_{\text{ff}} \Lambda(T)}
\]

\[
L_X(<R) \lesssim \int_0^R 4\pi r^2 \Lambda \left( \frac{3kT}{10 t_{\text{ff}} \Lambda} \right)^2 dr
\]

\[
L_X(<R) \lesssim \frac{9\pi}{25} (kT)^2 \Lambda^{-1} \sigma_v^2 R
\]
Precipitation-Limited Luminosity
Precipitation-Limited Luminosity

- Multiphase ACCEPT Cluster Cores (0.04$R_{500}$)
- Single Phase ACCEPT Cluster Cores (0.04$R_{500}$)
- Multiphase Werner Ellipticals
- Single Phase Werner Ellipticals
- NGC 4261
- MASSIVE Survey ($R_e$)
- ATLAS$^{3D}$ Survey ($R_e$)
- Nebular Emission
- CO Detection
- Milky Way (8 kpc)

Parameters:
- $t_{cool}/t_{ff}$
- $L_x(R)/R$ kpc$^{-1}$
- $kT_x$ (keV)

Equations:
- $L_x(R)/R$, $t_{cool(< R_e)} = 1$ Gyr
- Goulding+16 Galaxies ($R_e$)
- Panagouilta+14 Entropy Profile

Survey:
- Galactic Survey (8 kpc)
- Goulding+16 Galaxies (Re)
- Panagouilta+14 Entropy Profile
- MASSIVE Survey ($R_e$)
- ATLAS$^{3D}$ Survey ($R_e$)
Precipitation-Limited Luminosity

Self-similar: $L \sim T^{3/2} \Lambda(T)$
Precipitation-Limited Luminosity

$L_X (\text{erg s}^{-1})$ vs. $kT_X$ (keV)

- Multiphase ACCEPT Cluster Cores (0.15$R_{500}$)
- Single Phase ACCEPT Cluster Cores (0.15$R_{500}$)

Self-similar: $L \sim T^{3/2} \Lambda(T)$

- Maughan+12 CC (0.15$R_{500}$)
- Maughan+12 NCC (0.15$R_{500}$)

$L_X(R_{s})$, $t_{\text{cool}}(<R_{s}) = 1 \text{ Gyr}$
Precipitation-Limited Luminosity

Self-similar: $L \sim T^{3/2} \Lambda(T)$

- Multiphase ACCEPT Cluster Cores ($0.15R_{500}$)
- Single Phase ACCEPT Cluster Cores ($0.15R_{500}$)
- XXL Galaxy Clusters ($R_{500}$)
- Sun+09 Groups ($R_{500}$)

Maughan+12 CC ($0.15R_{500}$)
Maughan+12 NCC ($0.15R_{500}$)

$L_X(R_e), t_{cool(<R_e)} = 1$ Gyr
**Precipitation-Limited Luminosity**

[Graph showing the relationship between $L_X$ (erg s$^{-1}$) and $kT_X$ (keV) with various data points and labels indicating different types of clusters and groups.]

- **Triangles**: Multiphase ACCEPT Cluster Cores ($0.15R_{500}$)
- **Down triangles**: Single Phase ACCEPT Cluster Cores ($0.15R_{500}$)
- **Circles**: XXL Galaxy Clusters ($R_{500}$)
- **Plus signs**: Sun+09 Groups ($R_{500}$)

*Self-similar:* $L \sim T^{3/2} \Lambda(T)$

- **REXCESS Clusters** ($R_{500}$)
- **XXL Clusters** ($R_{500}$)
- **Bharadwaj+15** ($R_{500}$)
- **Maughan+12 CC** ($0.15R_{500}$)
- **Maughan+12 NCC** ($0.15R_{500}$)

$L_X(R_e)$, $t_{cool(<R_e)} = 1$ Gyr
**Precipitation-Limited Luminosity**

Self-similar: $L \sim T^{3/2} \Lambda(T)$

- Multiphase ACCEPT Cluster Cores ($0.15R_{500}$)
- Single Phase ACCEPT Cluster Cores ($0.15R_{500}$)
- XXL Galaxy Clusters ($R_{500}$)
- Sun+09 Groups ($R_{500}$)
- Anderson+15 ($R_{500}$)
- REXCESS Clusters ($R_{500}$)
- XXL Clusters ($R_{500}$)
- Bharadwaj+15 ($R_{500}$)
- Maughan+12 CC ($0.15R_{500}$)
- Maughan+12 NCC ($0.15R_{500}$)

$L_X(R_e), t_{cool(<R_e)} = 1$ Gyr
Precipitation-Limited Luminosity

Self-similar: $L \sim T^{3/2} \Lambda(T)$
**Precipitation-Limited Luminosity**

- Multiphase ACCEPT Cluster Cores ($0.15 R_{500}$)
- Single Phase ACCEPT Cluster Cores ($0.15 R_{500}$)
- XXL Galaxy Clusters ($R_{500}$)
- Sun+09 Groups ($R_{500}$)
- Anderson+15 ($R_{500}$)
- Massive Spirals ($0.05 R_{200}-0.15 R_{200}$)
- MASSIVE Survey ($R_e$)
- ATLAS3D Survey ($R_e$)
- Nebular Emission
- CO Detection

![Graph showing the relationship between $L_X$ (erg s$^{-1}$) and $kT_X$ (keV)]
Precipitation-Limited Luminosity

- Multiphase ACCEPT Cluster Cores (0.15R_{500})
- Single Phase ACCEPT Cluster Cores (0.15R_{500})
- XXL Galaxy Clusters (R_{500})
- Sun+09 Groups (R_{500})
- Anderson+15 (R_{500})
- Massive Spirals (0.05R_{200}-0.15R_{200})
- MASSIVE Survey (R_e)
- ATLAS^{3D} Survey (R_e)
- Nebular Emission
- CO Detection
- Milky Way (100 kpc)
- Milky Way (8 kpc)

- REXCESS Clusters (R_{500})
- XXL Clusters (R_{500})
- Bharadwaj+15 (R_{500})
- Maughan+12 CC (0.15R_{500})
- Maughan+12 NCC (0.15R_{500})
- Goulding+16 Galaxies (R_e)

\[ L_X (\text{erg} \, s^{-1}) \]

\[ kT_X (\text{keV}) \]

\[ t_{\text{cool}}/t_{\text{ff}} \]
Lynx high-resolution imaging of high S/N cluster sources

- Cavities will be detectable with 1” PSF and larger collecting area than Chandra.
- Zhuraleva/Churazov fluctuation analysis ($dT/T$ vs. $dn/n$) will be possible with a local sample of clusters: how is the CGM in clusters heated?
- Fluctuation analysis will probe smaller scales (more reliable quantification of turbulence).
- Velocities and velocity-widths of order 100 km/s will be of interest.
Lynx high-resolution profiles for hot gas in galaxies with and without AGN and cold gas

- Resolving hot gas profiles to radii close to the AGN (<1 kpc) gives important discriminants between wind-stabilized atmospheres and marginally precipitating ones.
- May be able to detect and measure bubbles around the AGN and in the CGM
- Simulations will be important for planning and interpreting observations: backgrounds and binary/AGN contamination will be significant sources of noise.
summary

• Multiphase gas halos around BCGs are the source of fuel for AGN and SF.

• Gas halos around BCGs are regulated primarily by AGN feedback.

• AGN feedback, done right, makes the entropy profile less steep but does not flatten or invert it (except temporarily or very close in).

• Applying the precipitation scenario to lower-mass galaxies predicts the MAXIMUM X-ray luminosity of a halo over 8 orders of magnitude of X-ray luminosity.

• One testable hypothesis: Galaxies closest to this limit will be more likely to have multiphase gas.

• Simulation development at cosmological scales is required: the “recipes” for feedback even a couple of years ago are falsified by X-ray data already. But to explore effects of duty cycle, galaxy interactions, magnetic fields, environment, we will need simulations.