Thermal Instability in Hot Halos

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Introduction

SOME GALAXY CLUSTERS contain long, thin ***filaments of cold gas*** embedded in an otherwise hot plasma—a surprising phenomenon, since cold gas should quickly heat up and evaporate.

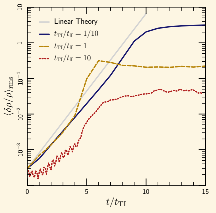
We explore how ***thermal instability***—a runaway cooling process—can generate and sustain these cold structures within hot halos. Crucially, we find that this process only occurs in regions where ***cooling beats gravity:*** the instability develops only when the *cooling time drops below the free-fall time*, or when $t_{\rm cool}/t_{\rm ff} \lesssim 10$.

This threshold not only explains when and where cold gas forms, but may also **regulate feedback** from black holes in cluster centers—helping to control the structure and evolution of massive galaxies.

Overview

- **Globally stable, locally unstable:** Even when the intracluster medium (ICM) is globally heated and stable, it can be locally unstable.
- **Nonlinear outcome depends on cooling vs. gravity:** The instability only grows if cooling outpaces infall: $t_{\rm cool}/t_{\rm ff} \lesssim 10$
- **AGN feedback and thermal regulation:** If cold gas fuels black hole activity, this instability acts as a **thermostat**, keeping the halo close to the critical threshold. This introduces a density "core" and explains the observed deviations from self-similarity.

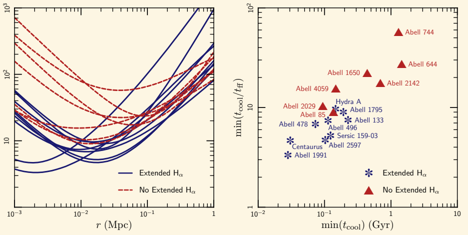
Non-Linear Saturation



THIS FIGURE illustrates the full development of thermal instability. The perturbations initially grow exponentially, but saturate at an amplitude which depends on the ratio of the cooling time to the free-fall time $t_{\rm cool}/t_{\rm ff}$. This amplitude can be > 1 or < 1. Thus, even exponentially-growing ***linear instability need not produce multi-phase gas***.

Intuitively, the instability stops when the infall time for an over-dense blob approaches its cooling time—shear instabilities then develop on a competitive timescale with thermal instability and can mix the gas. This competition sets the amplitude of the density perturbations.

Comparison with ACCEPT Data

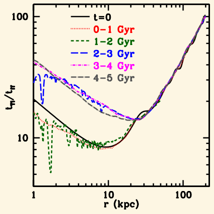


CONSISTENT WITH OUR MODEL, clusters in the ACCEPT catalog only show multi-phase gas below a threshold in $t_{\rm cool}/t_{\rm ff}$. Moreover, most multiphase gas is located within ~10–20 kpc, where this ratio reaches a minimum.

The ratio $t_{\rm cool}/t_{\rm ff}$ is a better predictor of multi-phase gas than $t_{\rm cool}$ alone.

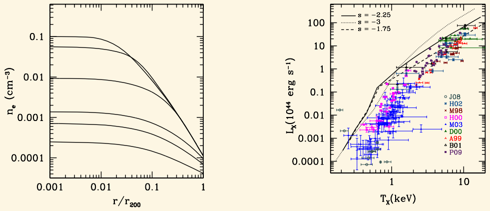
Feedback Regulation

THERMAL INSTABILITY may power AGN feedback in galaxy groups and clusters. Since the accretion rate from infalling clumps can vastly exceed accretion from the hot phase, the onset of thermal instability triggers powerful heating episodes. ***Our simulated halos self-regulate to the critical threshold for thermal instability, with $t_{\rm cool}/t_{\rm ff} \sim 10$.***



In this simulation, thermal instability develops during the first Gyr and produces clumps of cool gas. When the clumps reach the center of the halo around 2 Gyr, they trigger feedback and heat the gas above the threshold for non-linear stability. This removes the fuel source for AGN heating and the gas settles into a quasi-equilibrium.

Breaking Self-Similarity

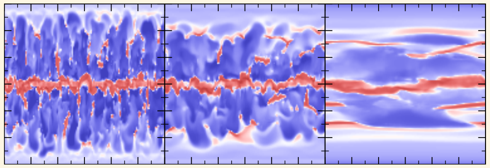


THE THRESHOLD for non-linear thermal stability thus limits the density of the gas below the prediction of gravitational self-similarity. ***Our criterion correctly predicts the "excess" entropy observed in groups and low-mass clusters, as well as the observational luminosity–temperature relation.***

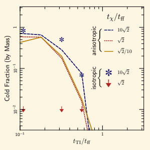
What About Conduction?

OF COURSE, conduction can suppress thermal instability on small scales. Crucially, however, thermal conduction in clusters is *anisotropic:* since electrons cannot cross magnetic field lines, they only transport energy in the direction of the field.

The figure below compares simulations with different values of the conductivity and shows that thermal instability is not suppressed in the direction perpendicular to the magnetic field.



Although conduction significantly changes the *morphology* of the thermally unstable gas (clumps → filaments), in practice it has little effect on the mass in the cold phase.



Thus, anisotropic conduction is *very different* from isotropic conduction, which readily suppresses thermal instability. This figure compares simulations with isotropic and anisotropic conduction.

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References

McCourt et al. (2012), Sharma et al. (2012a,b), Sharma et al. (2010)