Thermal Instability in Hot Halos

Mike McCourt, Prateek Sharma, Eliot Quataert, & Ian Parrish

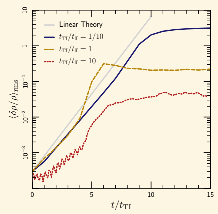
Introduction

To be, or not to be, that is the question: Whether 'tis Nobler in the mind to suffer The Slings and Arrows of outrageous Fortune, Or to take Arms against a Sea of troubles, And by opposing end them: to die, to sleep No more; and by a sleep, to say we end The heart-ache, and the thousand Natural shocks That Flesh is heir to? 'Tis a consummation Devoutly to be wished. To die to sleep, To sleep, perchance to Dream; Ay, there's the rub, For in that sleep of death, what dreams may come, When we have shuffled off this mortal coil, Must give us pause. There's the respect That makes Calamity of so long life: For who would bear the Whips and Scorns of time, The Oppressor's wrong, the proud man's Contumely,

Overview

- Assuming that the ICM in galaxy groups and clusters is globally stabilized by heating, it is *locally thermally unstable*. This is true even if thermal conduction is rapid.
- The non-linear saturation of thermal instability is controlled by the ratio of the cooling time to the free-fall time. The instability produces multi-phase gas only when $t_{\rm cool}/t_{\rm ff} \lesssim 10$
- If thermal instability powers AGN feedback, halos should self-regulate to the critical threshold for non-linear stability: $t_{\rm cool}/t_{\rm ff} \sim 10$. In practice, this introduces a density "core" and explains the observed deviations from gravitational self-similarity

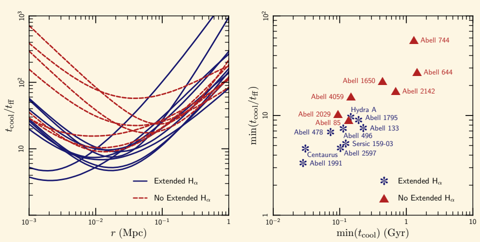
Non-Linear Saturation



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, ***linear thermal 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

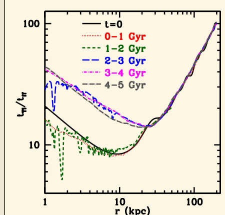


Consistent with our model, clusters in the accept catalog only show multi-phase gas below a threshold in $t_{\rm cool}/t_{\rm ff}$. Moreover, most multiphase gas is located within ∼10–20 kpc, where this ratio reaches a minimum.

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

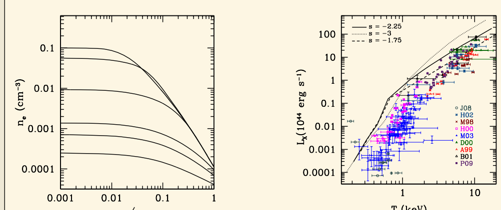
Feedback Regulation

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 $t_{cool}/t_{ff} \sim 10$.***



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

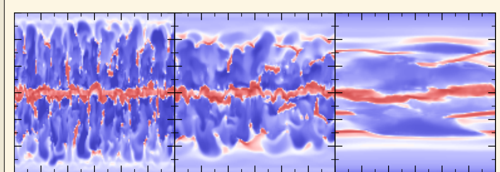


The threshold for non-linear thermal stability thus limits the density of the gas below the prediction of gravitational self-similarity. ***Our criterion correctly predicts the "excess" entropy observed in groups and low-mass clusters, as well as the observational luminosity–temperature relation.***

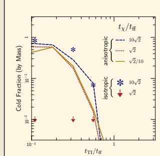
What About Conduction?

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)