# ACTIVE GALACTIC NUCLEI THERMAL HEATING

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## ABSTRACT

## 1. INTRODUCTION

Most galaxy clusters in the universe have active galactic nuclei (AGN) at the center of the cluster. These AGN play a significant role in the evolution of the cluster, affecting the structure, quenching star formation, etc. ***FG: References***

Feedback from AGN into the surrounding galaxy cluster has also been accepted as the primary mechanism behind keeing cool-core clusters thermally stable in the cool-core problem. Many galaxy clusters in the universe have been shown through x-ray observations to have cooling times much shorter than the free-fall time. Supernove, star formation, and other effects are insufficent to heat the cluster enough to prevent a cooling catastrophe and collapse. AGN, however, can output enough energy through thermal and kinetic feedback to prevent the collapse. Many recent simulations have shown that AGN activity triggered through a number of mechanisms, including cold gas, can raise the core entropy and prevent cooling.

•Constraints on AGN Feedback - self regulating?

•Elaborate on Voit analytical work - the toy model - a heating curve balancing cooling that preserves the entropy profile

In cosmological simulations, AGN feedback is modeled using a subgrid process. Due to the short timescale and small spatial scale evolution of the SMBH comprising the AGN compared to the larger galaxy cluster, it is impossible to coevolve the cluster and AGN simultaneously.

•AGN feedback in other simualtions

Much recent work has been done to better physically motivate these subgrid models to produce reasonable galaxy clusters. Triggering mechanisms explored include ... The feedback back mechanism has also had a great effect on the evolution of the cluster. Previous work by Meece Jr (2016) found that for feedback near the cluster core a non zero kinetic feedback component was needed to have a self regulating AGN; thermal heating alone in th e immediate radius around the AGN was insufficient to keep the cluster thermally stable;

• ***FG: Elaborate on Greg's work?***

This work builds on Meece Jr (2016), simplifying the feedback mechanism by extending the radius of feedback to a much larger radius.

•Paper outline/roadmap

Galaxy clusters have predictable entropy profiles whose shape (although not necessarily normalization) are mass-independent. Cavagnolo et al. (2009) Although -ray observations of the intracluster medium (ICM) indicate that the central cooling times in some galaxy clusters are much shorter than the age of the universe, no cooling catastrophe is observed. This argues that there is a heating mechanism that offsets the cooling and acts on timescales comparable to the cooling time. Given a variety of physical considerations, the primary heating source is largely accepted to be active galactic nuclei (AGN). What is not well-understood, however, is the manner in which AGN deposit energy into the ICM. **The goal of this work** is to constrain the radial dependence of the AGN energy injection by comparing a simplified model of AGN heating with key X-ray observable quantities. This effort builds on work by Meece et. al. Meece Jr (2016); Meece et al. (2017) using an idealized model of thermal feedback over the cluster core following a power law, inspired by analytical work by Voit et. al. Voit et al. (2017).

## 2. METHODOLOGY

### 2.1. *AGN Feedback*

•Energy from the AGN is deposited as purely thermal energy in a sphere encompassing the cluster. The thermal feedback follows a power law with radius, so that in general, $\dot{e}(r) \propto r^{-\alpha}$. However, this led to several numerical challenges, including a feedback that asymtopes to infinity at the AGN and a sharp cutoff in energy at the boundaries of the simulation. These were overcome by adding a minimum radius smoothing length $r_{\rm min} = 1$ kpc (comprising ***FG: FIXME*** cells on the highest refinement) and an exponential decay at a cutoff radius $r_c = 1$ Mpc. The full form of the feedback in erg s$^{-1}$ cm$^{-3}$ follows

$$\dot{e}(r) = \frac{\dot{E}(t)}{A} \begin{cases} \left(r_{\rm min}/r_c\right)^{-\alpha} \exp\left(-r_{\rm min}/r_c\right) & , \quad r <= r_{\rm min} \\ \left(r/r_c\right)^{-\alpha} \exp\left(-r/r_c\right) & , \quad r > r_{\rm min} \end{cases}, \quad (1)$$

where $\dot{E}(t)$ is the total energy feedback from the energy at time $t$ and $A$ is a scalar to normalize the feedback which is just the integral of the feedback function over the entire feedback radius. Higher values of $\alpha$ correspond to more centralized feedback around the AGN. Without the inner smoothing length, and $\alpha >= 3$ is unnormalizable, corresponding to infinitie energy feedback at the origin.

The total AGN heating rate $\dot{E}(t)$ tracks the total cooling rate within the cluster, which is updated every 10 Myr using `yt` to compute the total xray cooling.

•Conic feedback. When the spherically symmetric feedback models failed to maintain thermally stable galaxy clusters, we also investigated an additional feedback model with a conic feedback. The conic feedback for $r > r_{\rm min}$followed

$$\dot{e}(\theta) \propto \cos^2\theta \quad (2)$$

where $\theta$ is the polar angle. Within $r <= r_{\rm min}$, however, the conic dependance was removed, as it would otherwise produce disontinuities across the AGN. The normalization factor $A$ was also updated accordingly.

Energy from AGN feedback is deposited thermally in a sphere encompassing the cluster. The deposited energy fol-

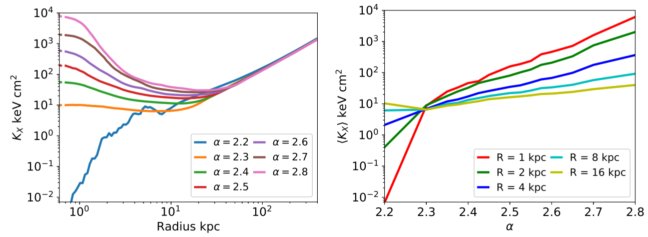


**Figure 1. Left:** Mean entropy as a function of spherical radius from several representative simulations with spherical feedback. **Right:** Mean cluster core entropy calculated within impact parameters ranging from $R = 2^0 - 2^4$ proper kpc for the same set of simulations, as a function of $\alpha$. In both panels, entropy is calculated by the mass-weighted temperature and the volume-weighted density, and all data is taken after 700 Myr of simulation evolution.

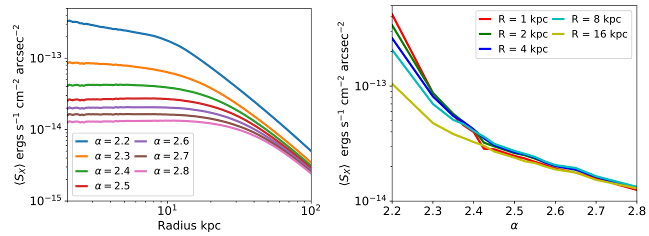


**Figure 2. Left:** Mean simulated X-ray surface brightness in the 0.5−2.0 keV band as a function of observing radius with spherical feedback. **Right:** Mean surface brightness of cores of radii $R = 2^0 - 2^4$ proper kpc from the same simulations as a function of $\alpha$. All data is taken after 700 Myr of simulation evolution.

lows a power law:

$$\dot{e}(r) \propto \left(\frac{r}{r_c}\right)^{-\alpha} \text{ erg s}^{-1}\text{ cm}^{-3}. \quad (3)$$

The thermal energy deposited in the cluster is scaled to exactly offset the total cooling within the cluster, thus maintaining overall energy balance. Simulations were run with a range of radial heating distributions ranging from $\alpha = 2.0$ to 2.9. All simulations used the adaptive mesh code `Enzo` Bryan et al. (2014) using AGN feedback algorithms modified from Meece Jr (2016); Meece et al. (2017).

We use a different $\alpha$ for each run, sampling from 2.0 to 2.9 in 0.1 increments and 2.5 to 2.7 in 0.05 increments.

### 2.2. *Initial Conditions*

•Each simulation is run for 8Gyr, or appoximately 4 sound crossing times for the cluster.

Simulations are initialized in a Perseus-like configuration, in the manner of Meece Meece et al. (2017) and Li et al. Li et al. (2015)

## 3. RESULTS

•Feedback failed to self regulate nor preserve thermal stability. In all cases the core entropy slowly dropped over time until a clump of cold gas formed, at which point each simulation then went through a cooling collapse. As the total cooling in the cluster spiked, the AGN activity also spiked. If the simulation was able to continue through the collapse and AGN outburst, the subsequent cluster was left with an unphysically high entropy profile.

Figures and show the average core entropies of several simulations with spherical and conic feedback repectively. More centrally concentrated heating delayed the collapse, although these also produced unphysical entropy profiles.

•Core entropy increases with $\alpha$.

•Surface brightness decreases with $\alpha$.

•Conic feedback collapses faster with more regularity.

•Collimated outflows with conic feedback.

## 4. DISCUSSION

•Higher energy input into core leads to slower collapse times, larger flat entropy cores.

•Formation of multiphase gas leads to collapse?

Higher $\alpha$, corresponding to more energy input at the cluster core, predictably raised core entropy. Lower $\alpha$ left a flat entropy profiles closer to the initial conditions. The higher $\alpha$ simulations push out enough gas from the core to decrease x-ray brightness.

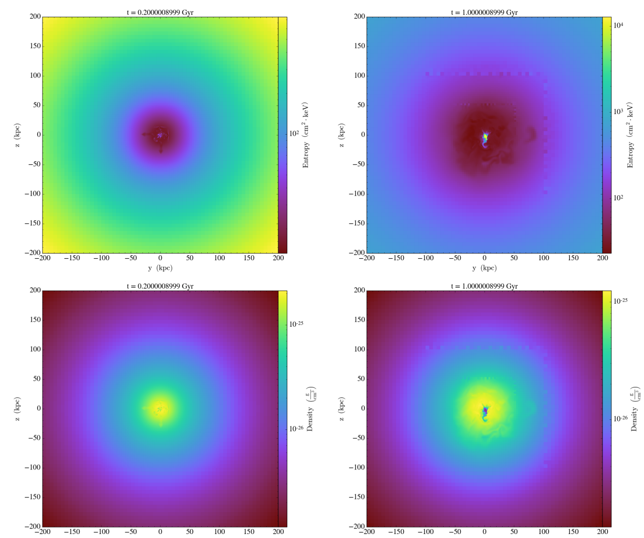


**Figure 3.** Entropy and density slices through the center of the the $\alpha = 2.2$ and $\alpha = 2.8$ simulations with spherical feedback at $t = 200$ Myr and $t = 1000$ Myr respectively.

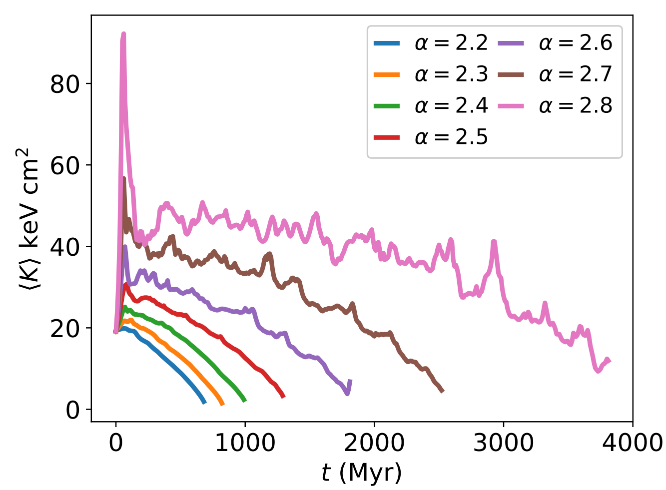


**Figure 4.** Mean core entropy on the inner 10 kpc as a function of time from several representative simulations with spherical feedback. evolution.

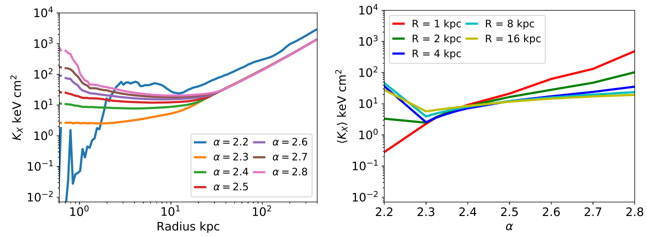


**Figure 5. Left:** Mean entropy as a function of conic radius from several representative simulations with conic feedback. **Right:** Mean cluster core entropy calculated within impact parameters ranging from $R = 2^0 - 2^4$ proper kpc for the same set of simulations, as a function of $\alpha$. In both panels, entropy is calculated by the mass-weighted temperature and the volume-weighted density, and all data is taken after 700 Myr of simulation evolution.

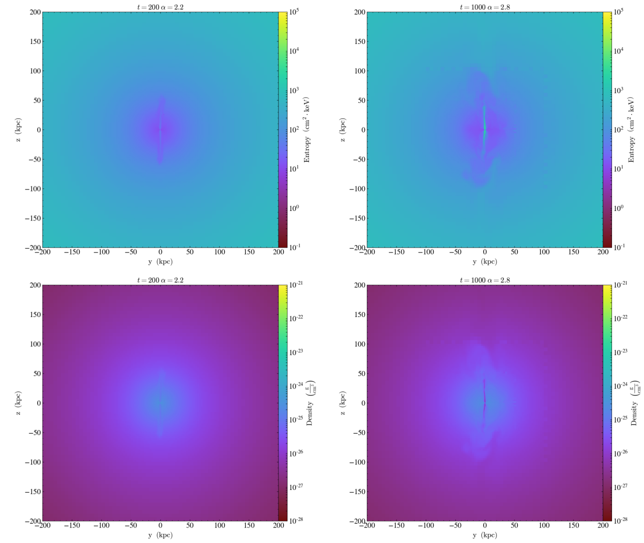


**Figure 7.** Entropy and density slices through the center of the the $\alpha = 2.2$ and $\alpha = 2.8$ simulations with conic feedback at $t = 200$ Myr and $t = 1000$ Myr respectively.

Although this is a very simplified model of cluster feedback, it can be used to constrain the broad properties of AGN feedback – in particular, the radial dependence of its heat deposition – using X-ray observations. In the near future, we will make direct comparisons to Chandra X-ray data of entropy and surface brightness profiles using the ACCEPT survey Cavagnolo et al. (2009) and its successors.

## 5. ACKNOWLEDGMENTS

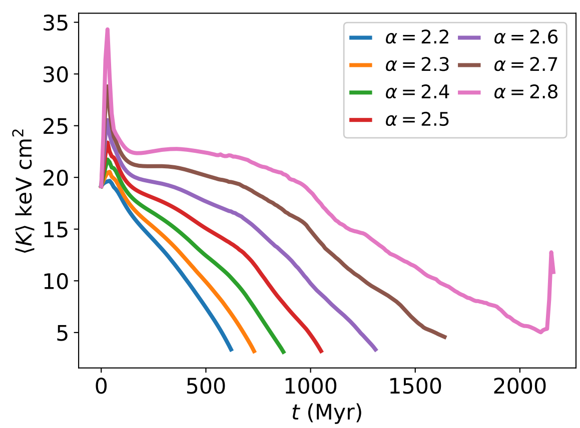


**Figure 8.** Mean core entropy on the inner 10 kpc as a function of time from several representative simulations with conic feedback. evolution.

**Figure 9.** Cold gas fraction as a function of time

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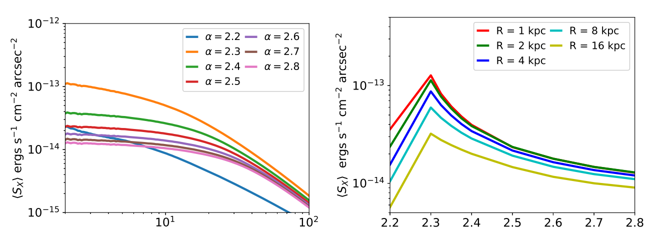


**Figure 6. Left:** Mean simulated X-ray surface brightness in the $0.5 - 2.0$ keV band as a function of observing radius with conic feedback. **Right:** Mean surface brightness of cores of radii $R = 2^0 - 2^4$ proper kpc from the same simulations as a function of $\alpha$. All data is taken after 700 Myr of simulation evolution.

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