

EFFECT OF ACTIVE GALACTIC NUCLEI THERMAL HEATING WITH RADIAL DEPENDENCE ON THERMAL STABILITY OF SIMULATED GALAXY CLUSTERS

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ABSTRACT

FG: Place holder abstract: Observations from the last decade have revealed the existence of cool-core clusters, galaxy clusters with a cooling time much shorter than the dynamical time. Recent work suggests that clusters may be thermally stable due to a central heating mechanism such as an active galactic nucleus (AGN) that prevents cooling. Previous analytical work in one dimension has shown that thermal heating from a central AGN with a power-law radial profile, where the heating exceeds cooling at near and far radii but not in an intermediate region, may produce a stable cluster with an isentropic entropy profile in the core and an isothermal profile outside the cluster. To test this, we simulated idealized galaxy clusters using the ENZO code with thermal heating from a central AGN. Thermal heating as a function of radius was injected proportional to the radius to a fixed exponent in $(-3, -2]$ for each run. Total thermal feedback was set equal to the total rate of cooling in the cluster. Thermal feedback with a conic angular dependence was also explored. However, the purely thermal feedback was not enough to achieve thermal stability and each simulation collapsed due to overcooling. These simulation results support previous work showing that kinetic feedback through a jet in addition to thermal feedback is necessary for self-regulating AGN activity.

1. INTRODUCTION

Active galactic nuclei (AGN,) the super massive black holes at the center of galaxy clusters, are the current most accepted theory for the explanation of cool-core (CC) clusters, galaxy clusters with a peaked X-ray surface brightness. The surface brightness of CC clusters indicate that they are radiating away large amounts of energy away quickly enough that they should have cooling times on the order of 10's of millions of years. This rapid cooling should lead to the condensation of cold clumps of gas within the clusters leading to star formation rates much greater than what is observed. They should collapse quickly within a couple million years, however CC clusters have lifetimes greater than billions of years and constitute roughly half the observed galaxy clusters in the universe. This set of problems is referred to collectively as the "cooling catastrophe." Since CC cluster are common and appear to be stable for at least billions of years, some mechanism must be counteracting the cooling by heating up the core of the cluster and quencing star formation.

Many sources of heating have been explored, including galaxy cluster mergers, cosmic rays, supernovae, and AGN. With the exception of AGN, these sources either do not provide enough heat to offset the cooling or do not heat the cluster on a frequent enough time scale. Observations indicate that the source of heating closely balances the cooling even on short time scales, suggesting a tight coupling between the heating and cooling. Work beginning with (Gaspari et al. 2011) and later by (Li et al. 2015) and (Meece et al. 2017) demonstrated self-regulating AGN in hydrodynamic simulations of idealized galaxy clusters. All of the simulations used either or both cold-gas and bondi accretion triggered feedback through thermal deposition around the AGN and bipolar outflows from the AGN. Many parameters of this model have been explored, although there is unified agreement for the need of kinetic outflows from AGN Meece Jr (2016); Meece et al. (2017). These AGN regulated the cooling and formation of cold gas within the cluster as well as reproducing temperature, density, and entropy profiles that match obser-

vations, including the isentropic multiphase core observed in the $R \approx 100$ kpc of galaxy clusters Gaspari et al. (2012).

The current working model of AGN feedback was built on this simulation work and previous observations Voit et al. (2017); Gaspari et al. (2017); Gaspari & Sądowski (2017). The AGN sits in the middle of a $R \approx 100$ kpc isentropic, thermally and convectively unstable core of multiphase gas at the center of the galaxy cluster. Cold clumps of gas condense out of multiphase region and precipitate onto the black hole. The accretion of cold gas onto the AGN triggers feedback through thermal heating around the AGN and kinetic outflows on a larger scale away from the AGN. This feedback maintains the isentropic core and ejects cold clumps of gas into the power-law region of the entropy profile where condensation and overcooling is suppressed. Through cold gas accretion the AGN heating is tightly coupled to the cooling rate while the kinetic outflows disrupt overcooling in the cluster.

However, this model is based on hydrodynamic simulations using simplified AGN feedback while in reality AGN feedback and particularly how the energy thermalizes occurs through a number of effects. These range from turbulent heat diffusion Ruszkowski & Oh (2011), viscous dissipation of waves generated by the AGN Ruszkowski et al. (2004), weak shocks and viscously dissipating sound waves Fabian et al. (2003), cosmic rays through a number of processes Guo & Oh (2008); Ruszkowski et al. (2017), dissipation of expanding bouyant bubbles created by the AGN Churazov et al. (2001), and many more processes involving turbulence and magnetized plasmas. Although these mechanisms may be necessary to fully model realistic self-regulating AGN in cool-core clusters,

Rather than explore the details of the AGN feedback, this work attempts to further simplify the AGN feedback in order to probe the theoretical model. We abstract the AGN feedback as just thermal heating set equal to the total cooling within the galaxy cluster. We explore a power-law radial dependence to deposit the right amount of energy in each part of the cluster to acheive thermal stability with the initial entropy profile.

Following (Voit et al. 2017), the heating needs to exceed the cooling within the inner core and at large radii, but for the cooling to exceed the heating at intermediate radii where the entropy profile switches from isentropic to a power-law. The multiphase gas should form in the isentropic region, in which cold clumps of gas will condense. The heating in the center pushes these clumps out of the core.

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.

2. METHODOLOGY

2.1. Simulation Setup

We ran several simulations of idealized galaxy clusters with a simplified AGN heating model using the cosmology code Enzo Bryan et al. (2014). We used the ZEUS solver for hydrodynamics Stone & Norman (1992), due to its robustness to evolve through discontinuities in the fluid around the AGN with sharply peaked thermal injection. Tabulated cooling was used to model radiative cooling following (Schure et al. 2009), assuming a metallicity of half the solar metallicity. The cooling table has a temperature of 10^4 K, however any processes below this temperature will take place on smaller scale than our spatial resolution. We used a fixed NFW profile for the gravitational potential and ignored self-gravity. Cosmological expansion was also ignored.

The simulations were run on a 3.2 Mpc cube with 64^3 cells in the base grid of the AMR hierarchy with a maximum of 8 levels of refinement, making the minimum cell size approximately 195 pc. The mesh was refined at high gradients in the fluid and high baryon density. Additionally, a 4 kpc cube grid centered on the AGN was fixed at the maximum level of refinement.

Each simulation was initialized with temperature and density profiles similar to the Perseus Cluster following (Li & Bryan 2012) and (Meece et al. 2017), which use analytical fits for the temperature profile from (Churazov et al. 2004) and (Vikhlinin et al. 2006) and slightly modified electron number densities following (Mathews et al. 2006). The initial pressure was computed from the temperature and density assuming an ideal gas with $\gamma = 5/3$. The mass giving the fixed gravitational potential has two components: an NFW halo profile and a BCG with a mass profile both following (Li & Bryan 2012), which includes both dark matter and baryonic matter and mimics observations of the Perseus Cluster. The entropy profile of the gas is initialized to

$$K(r) = K_0 + K_{100} (r/100 \text{ kpc})^{\alpha_K} \quad (1)$$

following results from the ACCEPT database (Cavagnolo

et al. 2009), using the definition for specific entropy

$$K \equiv \frac{kT}{n_e^{2/3}}. \quad (2)$$

Each simulation was set to run for 8 Gyr, approximately 4 sound crossing times across the cluster. However, almost all simulations were stopped hydrodynamics solver failed due to high feedback rates introducing discontinuities. A few simulations managed to evolve through the collapse and rebound but with observationally unreasonable final states.

Simulation results were analyzed using yt Turk et al. (2011).

2.2. AGN Feedback

In the simplified AGN feedback model used here, energy from the AGN is deposited as purely thermal energy in a sphere encompassing the cluster, with the total heating set equal to the total cooling in 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 issues, including a feedback that asymptotes 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 $r_{\min} = 1$ kpc (comprising 5 cells in radius on the highest refinement) and an exponential decay at a cutoff radius $r_c = 1$ Mpc. The full form of the volumetric feedback in $\text{erg s}^{-1} \text{cm}^{-3}$ is

$$\dot{e}(r) = \frac{\dot{E}(t)}{A} \begin{cases} (r_{\min}/r_c)^{-\alpha} \exp(-r_{\min}/r_c) & , \quad r \leq r_{\min} \\ (r/r_c)^{-\alpha} \exp(-r/r_c) & , \quad r > r_{\min} \end{cases}, \quad (3)$$

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 α correspond to more centralized feedback around the AGN. Without the inner smoothing length, and $\alpha > 3$ is unnormalizable, corresponding to infinite energy feedback at the origin.

The total AGN heating rate $\dot{E}(t)$ is set to the total cooling rate within the cluster. For simplicity, the heating rate is updated every 10 Myr using yt to compute the total cooling. Although the cooling rate increases exponentially up through the cooling collapse, the increase is slow enough so that the heating rate does not fall behind the true cooling rate by more than 1%.

We also investigated a conic feedback when the spherically symmetric feedback models failed to maintain thermally stable galaxy clusters. Outside of the smoothing length $r > r_{\min}$, the conic feedback had an additional term to the spherical feedback

$$\dot{e}(\theta) \propto \cos^2 \theta \quad (4)$$

where θ is the polar angle. Within $r \leq r_{\min}$, the conic dependence was removed in order to avoid discontinuities across the origin. The normalization factor A was changed to correctly scale the total heating.

Simulations were run with a range of radial heating distributions ranging from $\alpha = 2.0$ to 2.9. Initially the space of α was probed in increments of 0.1 before more values of α were explored between these values. The later values of α explored differ between the spherically symmetric and conic runs. The values of α explored are listed in table 1.

Figure 1.

Feedback Model	α 's explored
Spherical	2.0, 2.1, 2.3, 2.35, 2.375, 2.4, 2.425, 2.45, 2.5, 2.525, 2.55, 2.575, 2.6, 2.8, 2.9
Conic	2.0, 2.1, 2.2, 2.3, 2.325, 2.35, 2.375, 2.4, 2.5, 2.6, 2.7, 2.8

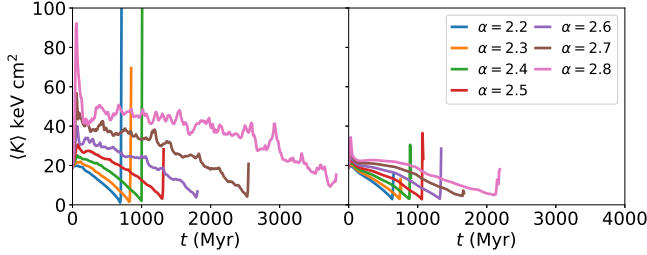


Figure 2. Mean entropy of the inner 10 kpc proper as a function of time for simulations with radial exponents ranging from $\alpha = 2.2$ to $\alpha = 2.8$ with spherical and conic feedback. Mean entropy is calculated by the mass-weighted temperature and the volume-weighted density. To improve visibility, these are plotted up until 30 Myr after the mean core entropy has increased by 60% in a 10 Myr span, or until the simulation has stopped. After this point, the entropy profile has diverged from what would be expected from observations. Simulations using values of α between those shown here were also run, although all exhibited the same core entropy decay with higher values of α decaying slower and conic feedback collapsing faster.

The AGN feedback algorithm used in this work relied heavily and upon and were modified from (Meece Jr 2016; Meece et al. 2017), using the active particle framework built in ();

3. RESULTS

Feedback failed to self regulate nor preserve thermal stability. For all choices of α with either spherical or conic feedback, the mean entropy of the inner 10 kpc core fell over time, eventually leading to a cooling driven collapse (fig. 2.) Each simulation formed a cold clump of gas in or near the core of the cluster (fig. ??) which began run away cooling and a spike in AGN activity to match the cooling (fig. ??). Most simulations halted due to hydrodynamics errors during this spike in feedback but a random selection of simulations managed to evolve through the collapse. However, these simulations had raised entropy profiles post-collapse which do not match observed entropy profiles of CC clusters.

3.1. High vs. Low α

There were some differences between simulations using low $\alpha < 2.5$ (more dispersed thermal deposition) and high $\alpha > 2.5$ (more centralized thermal deposition.)

The high α feedback raised core entropies higher above the initial entropy compared to low α runs by raising core temperatures and pushing out gas to lower electron densities (fig. ??), as expected.

The increased entropy in the core from increased energy deposition delayed the cooling driven collapse for a longer period of time. This was also an expected result. Looking at fig. 2, higher α delayed the collapse super-linearly compared to lower α . However, it should be noted that percent of the total feedback energy deposited in the core does not scale linearly with α but asymptotes exponentially as $\alpha \rightarrow 3$. Towards the limiting case as $\alpha \rightarrow 3$ the feedback will be constrained to a small $r < 5$ kpc core, similar to the thermal only feedback case from Meece et al. (2017), although the heating is triggered by the total cooling and not cold gas.

Additionally, by pushing more gas out of the core the cold clump that precedes collapse forms outside of $r = 1$ kpc in high

α runs while the cold clump forms in the center of the cluster in low α runs. However, this distinct separation of where the cold clump forms may be due to high α runs reaching the density floor of the simulation in their centers.

FG: Make a footnote? Include in each plot? Most plots in this section are taken at $t = 500$ Myr, an arbitrary time step after the initial settling of the cluster and before collapse which demonstrates the approximate structure of each simulation. Before $t = 500$ Myr the higher α runs have not settled from the initial burst AGN activity while later than $t = 500$ Myr the lower α simulations have already collapsed. The two α values 2.2 and 2.8 are used as the most extreme values of α simulated that evolved to $t = 500$ Myr without collapsing.

Fig. 3 shows phase plots of entropy and the cooling rate versus radius. As expected, at $t = 500$ Myr the higher $\alpha = 2.8$ run has a higher core entropy than $\alpha = 2.2$ since more energy is deposited in the center. The median entropy profile still follows the initial median but there is more high entropy gas near the core. Both the spherical and conic $\alpha = 2.2$ evolved past their collapse but are left with core entropy profiles too high to match observations. The $\alpha = 2.8$ simulations formed cold gas near their cores as they collapsed before hydrodynamic errors stopped the simulations. The heating rate is also plotted with the median cooling in the cooling rate phase diagram. For certain values of α , heating exceeds cooling in the inner core and outer radii but not in the intermediate range where the entropy profile changes from a flat line to a power law. **FG: This would make more sense with volume averaged cooling rate instead of the median - that's what should be directly compared.** However, this criterion was not enough to produce thermally stable clusters.

Fig. 4 shows the entropy and surface brightness profiles of several simulations at $t = 500$ Myr with both spherical and conic feedback. High α and so more centralized feedback lead to elevated core entropies that slope up and away from the initial flat entropy core. The lower α simulations with more realistic entropy profiles **FG: (realistic?)**, however, collapse soon after reaching a flat core entropy. The lower surface brightness is likely due to the lower density in the core.

As expected, core entropy increases with α in fig. 5 due to the higher amount of energy deposited in the core. The core surface brightness diminishes with α , partly due to lower cooling rates and less massive cores as higher α pushes more mass out of the core. From examining different core sizes, the effect of different α is more visible for smaller cores for larger α . Note that the total heating in the core scales greater than linearly with α **FG: Check how this scales: is it exponentially?**

Fig. 6 shows slices through the origin of the entropy, density, temperature, and cooling rate of simulations with spherical and conic heating with $\alpha = 2.2$ and $\alpha = 2.8$, two more extreme values of α . In both high α simulations, the core entropy and temperature are raised while the core density and cooling rate is lower. In the conic simulations, the jet structure is more apparent in high α cases. The jet is also more collimated than would be expected for the $\cos^2 \theta$ dependence used, although this may be due to the small radius where the majority of the energy is deposited in the high α case.

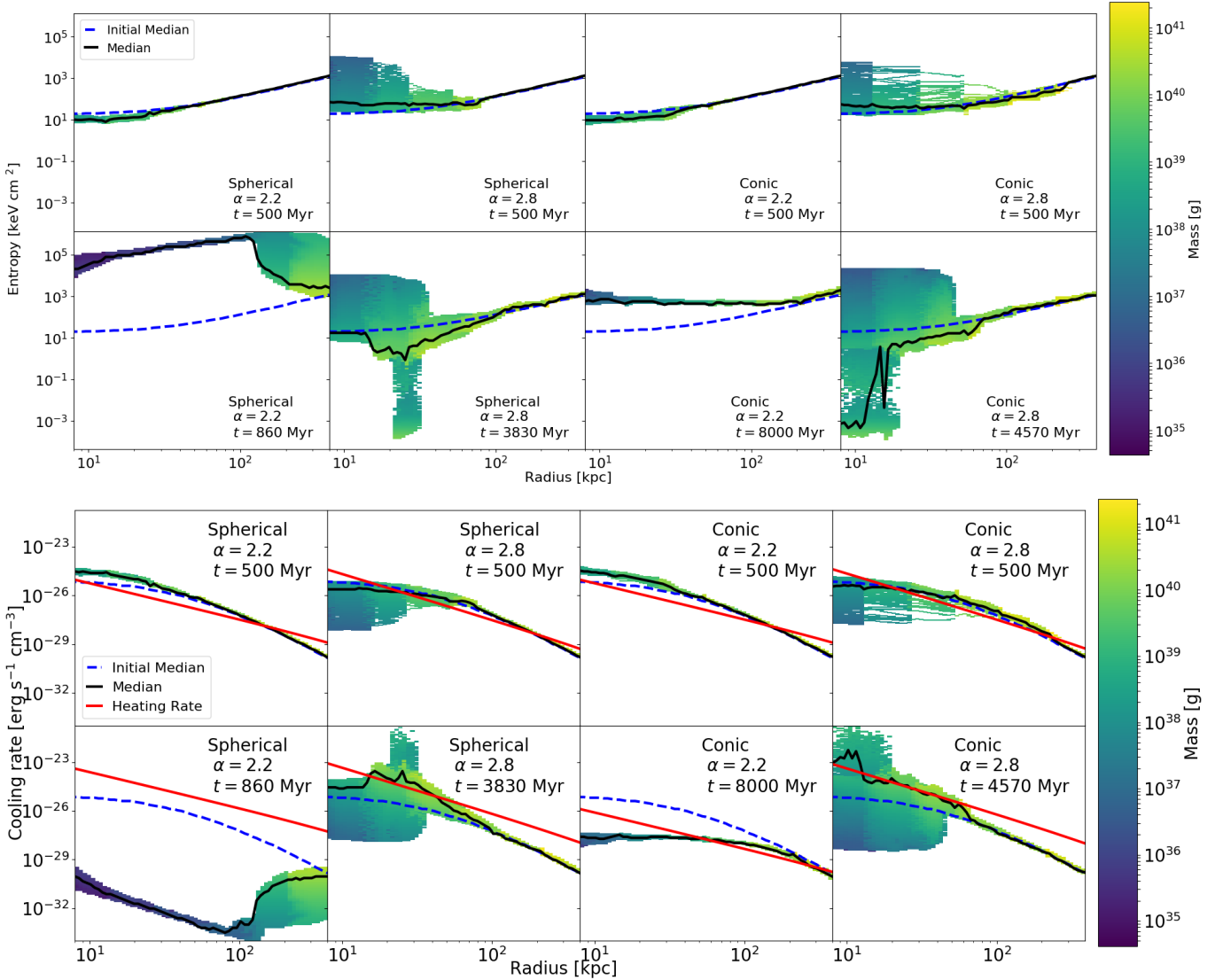


Figure 3. Phase plots of entropy and cooling rate versus radius of simulations with spherical and conic AGN heating with radial exponents $\alpha = 2.2$ and $\alpha = 2.8$ as labeled, with the initial and current median entropy or cooling rate versus radius in dashed blue and solid black respectively. The total heating rate in a shell versus radius is superimposed on the cooling rate in solid red, which is scaled in the simulation to match in total cooling rate. The upper plots are at $t = 500$ Myr and the lower plots are at the final time step of the simulation. *FG: Should I include the final step? Maybe more a time sequence through collapse of one simulation? Combine r axes. Also, maybe a radial profile of cold gas to see where it forms*

4. DISCUSSION

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

- Formation of multiphase gas leads to collapse?

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

5. SUMMARY

- No configuration of radial exponent α for purely thermal feedback with spherical nor conic feedback achieved thermal stability; all simulations collapsed during the formation of cold gas. The kinetic outflows from previous simulations may be irreplaceable with purely thermal feedback.

- Higher values of α , corresponding to more centralized feedback, increased core entropy, lowered core surface brightness, and delayed collapse. Conic feedback also hastened collapse.

- Higher values of α produces unreasonable entropy profiles compared to observations. These can be eliminated from simplified models of AGN feedback.

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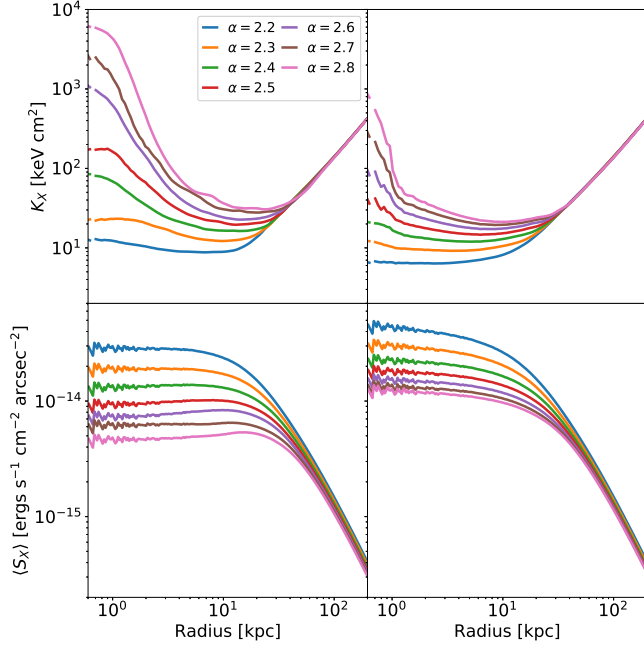


Figure 4. Top: Mean entropy as a function of spherical radius from several representative simulations using different radial exponents α for heating with spherical feedback (left) and conic feedback (right.) Mean entropy is calculated by the mass-weighted temperature and the volume-weighted density. **Bottom:** Mean simulated X-ray surface brightness in the 0.5–2.0 keV band as a function of observing radius from several representative simulations using different radial exponents α for heating with spherical feedback (left) and conic feedback (right.) All data is taken at $t = 500$ Myr. *FG: Add density? Add text annotations? Combine with fig. 5? Combine spherical and conic onto one plot?*

Enzo and yt are developed by a large number of independent researchers from numerous institutions around the world. Their commitment to open science has helped make this work possible.

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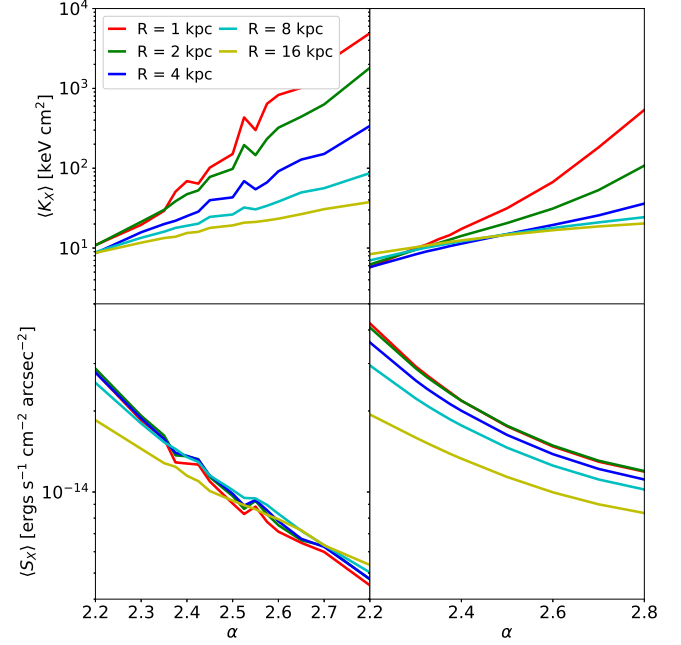


Figure 5. Top: Mean cluster core entropy calculated within impact parameters ranging from $R = 2^0 - 2^4$ proper kpc as a function of α for heating with spherical feedback (left) and conic feedback (right.) Mean entropy is calculated by the mass-weighted temperature and the volume-weighted density. **Bottom:** Mean simulated X-ray surface brightness in the 0.5–2.0 keV band of cores of radii $R = 2^0 - 2^4$ proper kpc from as a function of α for heating with spherical feedback (left) and conic feedback (right.) All data is taken at $t = 500$ Myr.

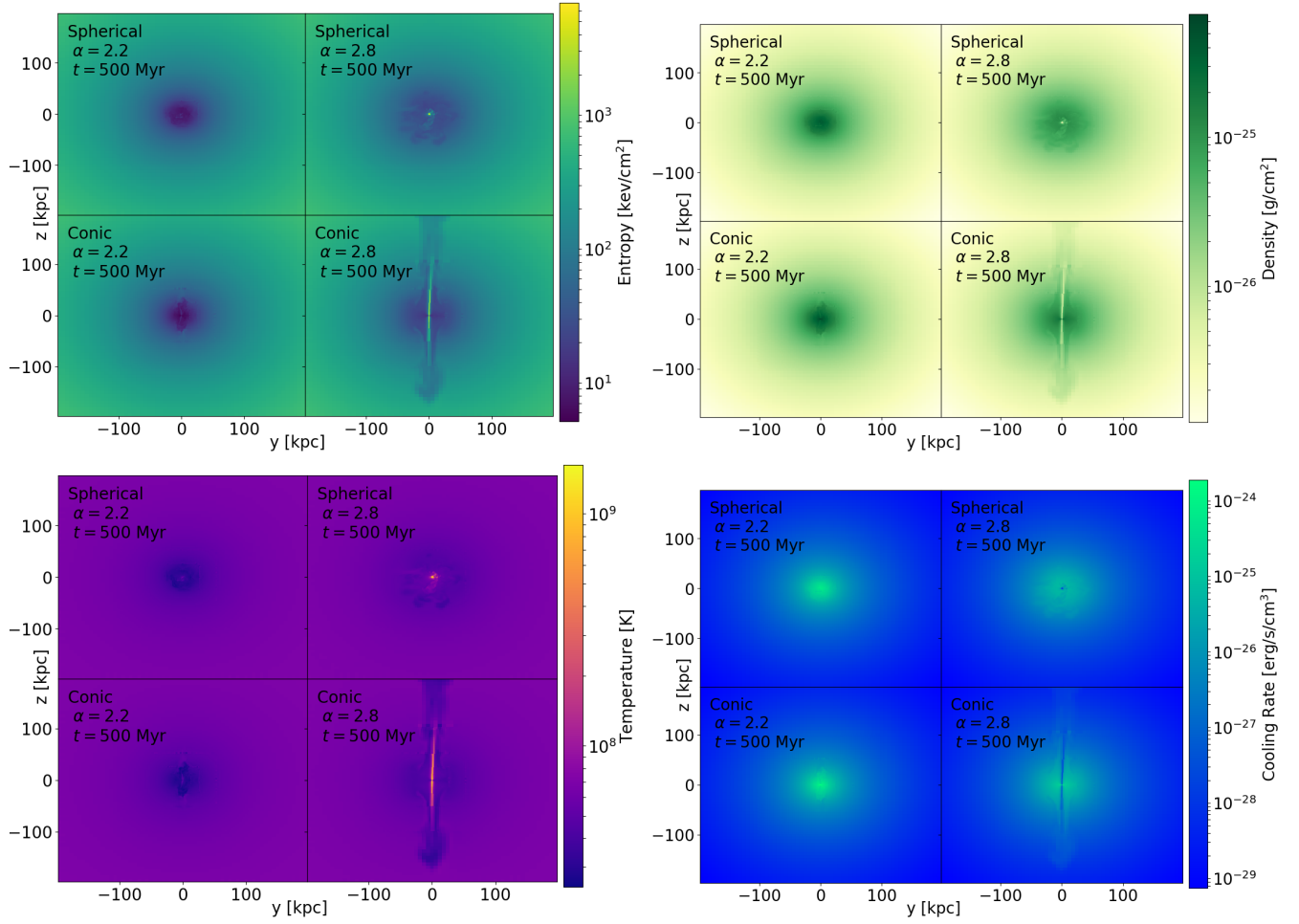


Figure 6. Slices of entropy, density, temperature, and cooling rate through the origin of simulations with spherical and conic AGN heating with radial exponents $\alpha = 2.2$ and $\alpha = 2.8$ as labeled. All data is taken at $t = 500$ Myr. *FG: Are these figures worth including? Combine x and y axes?*