DRAFT VERSION JUNE 29, 2018
Preprint typeset using LATEX style emulateapj v. 01/23/15

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

FORREST W. GLINES [1,2,3], BRIAN W. O'SHEA [1,2], G. MARK VOIT[1]
[1]Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
[2]Department of Computational Mathematics, Science and Engineering, Michigan State University, East Lansing, MI 48824, USA and
[3]glinesfo@msu.edu
Draft version June 29, 2018

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 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

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 keeping 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. Supernovae, star formation, and other effects are insufficient 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 simulations

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 $r_{\min} = 1$ 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

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

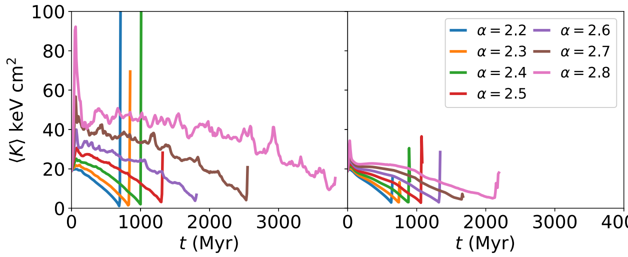

Figure 1. Mean entropy of the inner 10 kpc proper as a function of time for simulations with radial exponents ranging from $\alpha = 2.2$ to $\alpha = 2.8$ with spherical and conic feedback. Mean entropy is calculated by the mass-weighted temperature and the volume-weighted density. To improve visibility, 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.

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 $\dot{E}(t)$ tracks the total cooling rate within the cluster, which is updated every 10 Myr using `yt` to compute the total X-ray 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

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

where θ is the polar angle. Within $r <= r_{\rm min}$, however, the conic dependence was removed, as it would otherwise produce discontinuities 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 follows a power law:

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

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 α 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 approximately 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. Fig. 1 shows the mean core entropy of the inner 10 kpc as a function of time for several representative simulations. For all choices of α with either spherical or conic feedback, 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, as is shown in the entropy phase plots in fig. **??**.

High values of α, or more centrally peaked feedback, led the collapse to happen later. Although even higher values of α may prevent the collapse for longer, the central heating asymptotes to infinity as $\alpha \to 3$. A simulation with $\alpha = 2.9$ led to immediate discontinuities in the fluid that the hydrodynamics solvers were unable evolve. ***FG: Need to elaborate on this?*** Additionally, the higher α runs led to central entropies and surface brightnesses that are unreasonable from observations (see figs. 3 and 4.)

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. 2 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. 3 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. 4 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 expo-***

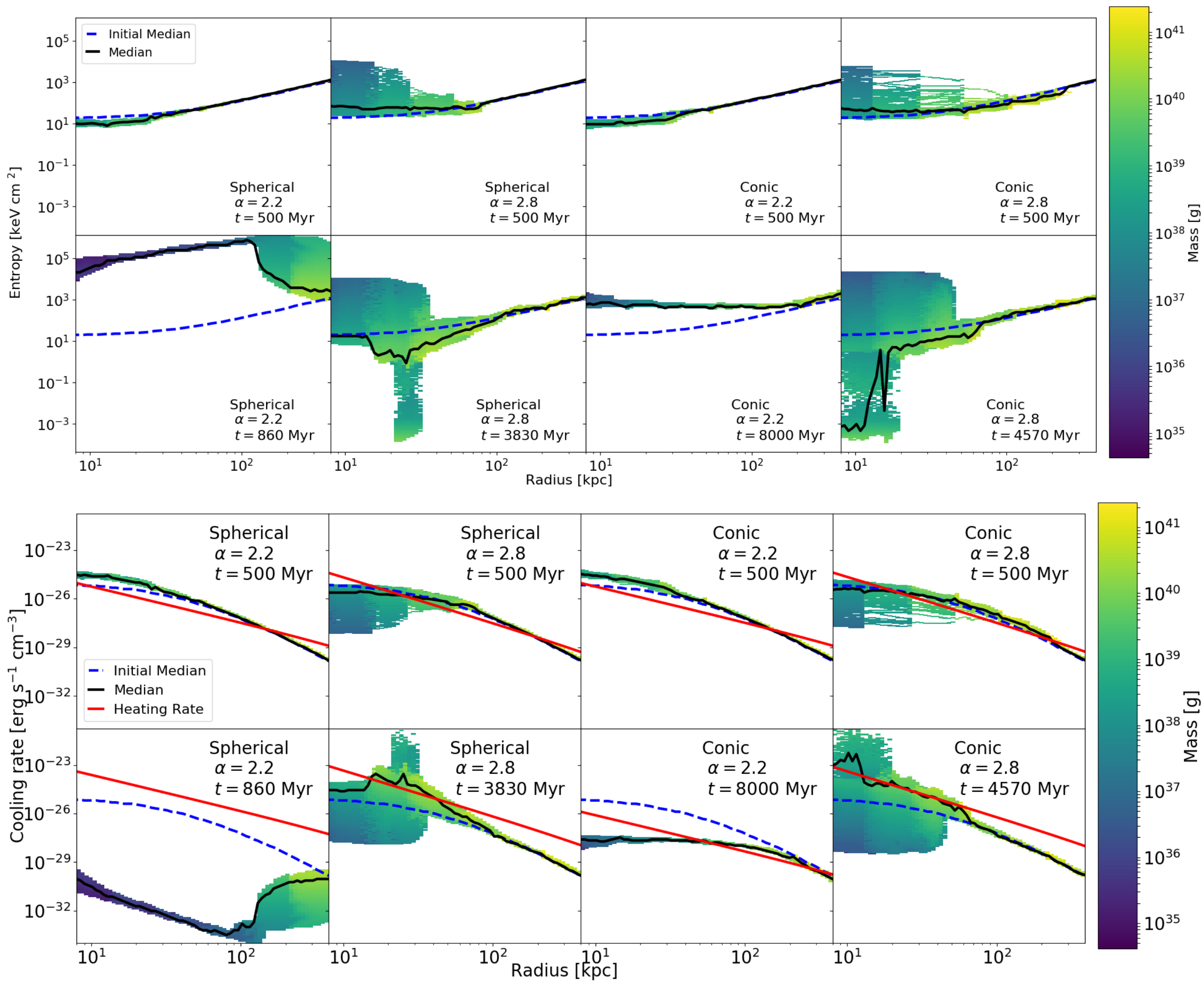

Figure 2. Phase plots of entropy and cooling rate versus radius of simulations with spherical and conic AGN heating with radial exponents $\alpha = 2.2$ and $\alpha = 2.8$ as labeled, with the initial and current median entropy or cooling rate versus radius in dashed blue and solid black respectively. 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***

nentially?.

Fig. 5 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.

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.

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. 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.
- Higher values of α, corresponding to more centralized feedback, increased core entropy, lowered core surface

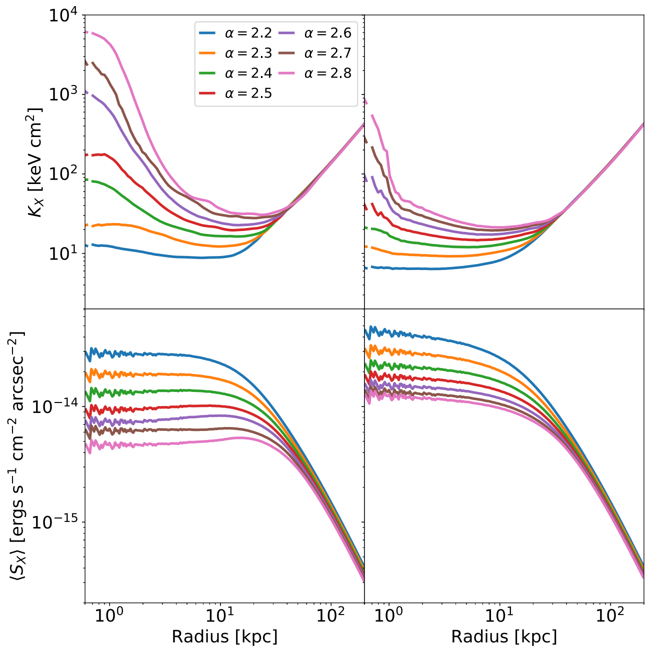

Figure 3. Top: Mean entropy as a function of spherical radius from several representative simulations using different radial exponents α for heating with spherical feedback (left) and conic feedback (right.) Mean entropy is calculated by the mass-weighted temperature and the volume-weighted density. **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. 4? Combine spherical and conic onto one plot?***

brightness, and delayed collapse. Conic feedback also hastened collapse.

6. ACKNOWLEDGMENTS

This project has been supported by NASA through Astrophysics Theory Program grant #NNX15AP39G and Hubble Theory Grant HST-AR-13261.01-A, and by the NSF through grant AST-1514700. The simulations were run on the NASA Pleiades supercomputer through allocation SMD-16-7720. `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.

REFERENCES

Bryan, G. L., et al. 2014, The Astrophysical Journal Supplement Series, 211, 19

Cavagnolo, K. W., Donahue, M., Voit, G. M., & Sun, M. 2009, The Astrophysical Journal Supplement Series, 182, 12

Li, Y., Bryan, G. L., Ruszkowski, M., Voit, G. M., O'Shea, B. W., & Donahue, M. 2015, The Astrophysical Journal, 811, 73

Meece, G. R., Voit, G. M., & O'Shea, B. W. 2017, The Astrophysical Journal, 841, 17pp

Meece Jr, G. R. 2016, AGN Feedback and Delivery Methods for Simulations of Cool-Core Galaxy Clusters (Michigan State University)

Voit, G. M., Meece, G., Li, Y., O'Shea, B. W., Bryan, G. L., & Donahue, M. 2017, The Astrophysical Journal, 845, 80

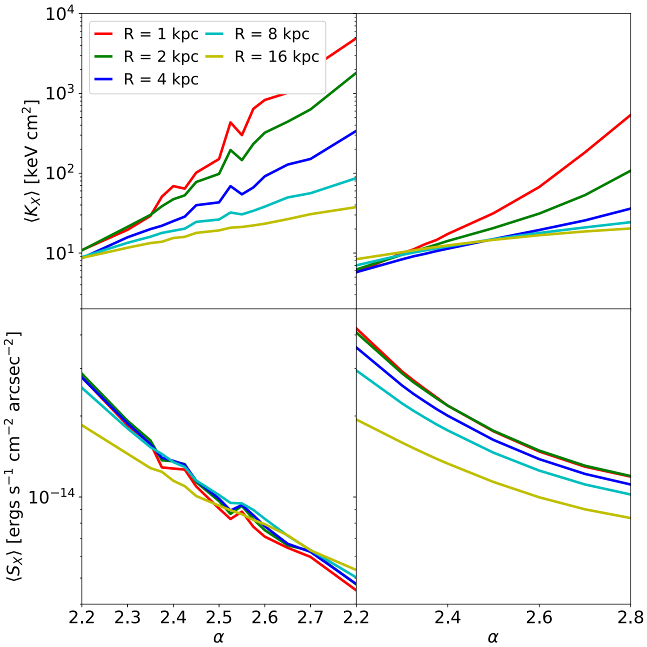

Figure 4. **Top:** Mean cluster core entropy calculated within impact parameters ranging from $R = 2^0 - 2^4$ proper kpc as a function of α for heating with spherical feedback (left) and conic feedback (right.) Mean entropy is calculated by the mass-weighted temperature and the volume-weighted density. **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 take at $t = 500$ Myr.

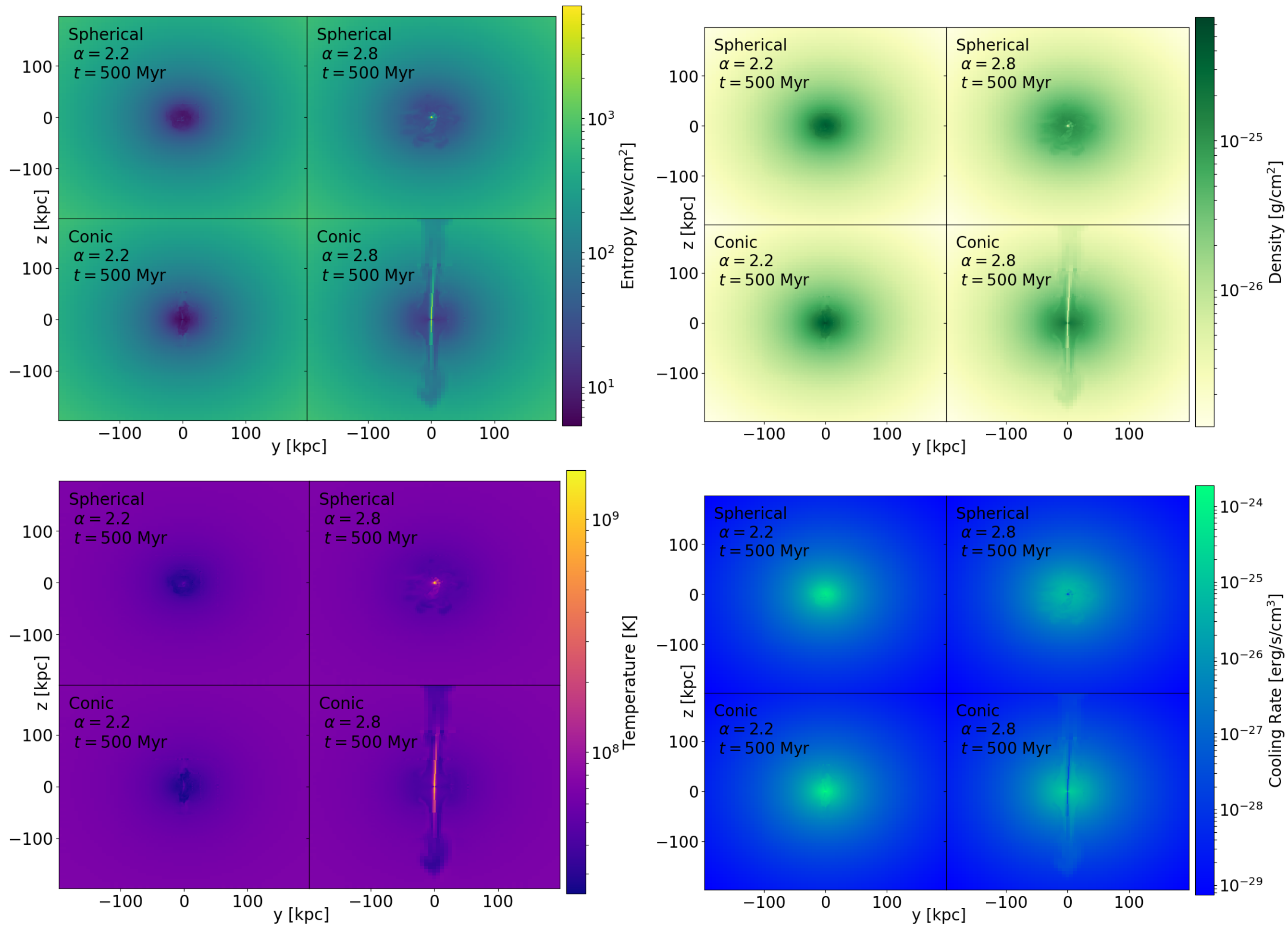

Figure 5. Slices of entropy, density, temperature, and cooling rate through the origin of simulations with spherical and conic AGN heating with radial exponents $\alpha = 2.2$ and $\alpha = 2.8$ as labeled. All data is taken at $t = 500$ Myr. ***FG: Are these figures worth including? Combine x and y axes?***