A Multiwavelength Study of Pre-AGN Outburst BCGs in X-ray Luminous Clusters and Groups of Galaxies

1 Motivation

The general process of galaxy cluster formation through hierarchical merging is well understood, but many details, such as the impact of feedback sources on the cluster environment and radiative cooling in the cluster core are not. The most massive baryonic component of a galaxy cluster is the intracluster medium (ICM) which has densities of a few 10^{-3} cm^{-3} and temperatures ranging $2 - 10$ keV. The ICM is observed as a luminous X-ray "cloud" which pervades the cluster over several cubic Mpcs, and has varying amounts of substructure which depend on the cluster dynamical state. Clusters which have not experienced a major merger event for a few Gyrs, the ICM is observed to be stratified, spherically symmetric, and in approximate hydrostatic equilibrium.

In the absence of processes other than gravity, all clusters will be scaled versions of each other with the defining characteristic being cluster mass. The mass of a cluster determines the depth of the gravitational potential well and the well depth in turn defines global cluster properties such as ICM luminosity and temperature. But the Universe does not operate so simplistically as to have gravity be the only process which defines a cluster's properties. Portions of the inhomogeneous ICM have cooling times shorter than the age of the Universe and are thus subject to radiative cooling. As the ICM radiatively cools, massive "cooling flows" of cold gas streaming to the bottom of the clusters potential well should result. But these cooling flows have never been observed with the predicted rates of hundreds to thousands of solar masses per year, instead the flows are more like trickles depositing at best a few solar masses per year in the core.

I must digress for a moment to introduce the concept of ICM entropy on which I rely heavily in this proposal. Density and temperature are not the truest representation of the ICM's physical state because they are most influenced by the underlying dark matter potential. These two quantities are therefore not ideal for understanding the thermal history of the ICM. But when we define a new quantity, $K = Tn^{-2/3}$, which we call entropy (but is in actuality the adiabatic constant), we have captured the gas thermal history because only heating and cooling can alter entropy. Compression and expansion of the ICM does not change K the way it affects temperature. Even better, the radial entropy distribution of the ICM is very telling because a potential well is like a giant entropy sorting device: the ICM is only convectively stable when $dK/dr \geq 0$. If a cluster were a sealed box of gravitation-only processes whom's core was dominated by a cooling flow, then the radial entropy distribution would strictly follow a power-law relation across all radii.

In my thesis I have conclusively proven that a central entropy pedestal (Fig. 1) is a universal feature of clusters. But what secondary process(es) removes low-entropy gas from the core of a cluster? Recently, bubbles blown in the ICM by AGN have been observed in numerous clusters ([1]). These bubbles contain the energy necessary to retard core cooling and thus to eradicate low-entropy gas in the core. In support of this AGN feedback framework is the picture of the ICM entropy-feedback connection emerging from my thesis. My work suggests BCG radio luminosity (Fig. 2) and BCG Hα emission (Fig. 3) are anti-correlated with cluster central entropy. I have found that clusters with central entropy $\leq$ 20 keV cm^2 exhibit star formation and radio AGN activity in the BCG while clusters above this threshold unilaterally do not have star formation and exhibit diminished AGN radio feedback. Corroborating observations of strong blue gradients as a function of decreasing central entropy in BCGs has also been seen by Rafferty et. al. (2007 in press).

A satisfactory solution to the cooling flow problem and flattening of entropy profiles has been found with AGN, but a nasty problem of these models has also emerged: **how does AGN feedback couple to ICM properties such that the system becomes self-regulating?** The central entropy level mentioned above, $K_0 = 20$ keV cm^2, is auspicious as it coincides with the Field length at which thermal conduction can stabilize a cluster core (Fig. 4). It is possible conduction is the physical mechanism by which ICM gas properties are coupled to feedback mechanisms such that the system becomes self-regulating. If an AGN outburst does not boost the ICM entropy of the core to greater than ~ 20 keV cm^2 then the core will not be subject to stabilization by conduction and cooling plus condensation will proceed, ultimately leading to future AGN outbursts and prodigious star formation in the BCG.

But while this framework is exciting, it needs refinement to produce a robust model which explains the fueling of AGN, resulting AGN heating, couples the ICM with AGN, and properly predicts the effect on BCG star formation rates. Observations of an AGN interacting with the hot cluster atmosphere (a very useful diagnostic) abound (i.e. [2]), but the best diagnostic – direct observation of on-going shock heating from a young AGN – are rare, most likely short-lived, or impossible to see because of observation resolution limits or gas and dust enshroudment. I suggest we attack the problem of understanding AGN feedback in clusters by inverting the problem. Instead of basing models only on observations of feedback *after* it has occurred, we should also add constraints by focusing on the cluster core environment *before* an AGN outburst is very near. But how does one go about selecting a sample of objects which we know to be near the beginning of a feedback cycle?

Looking closer at Figure 2 and Figure 3 you will notice blue boxes with red stars. These points indicate clusters with BCGs which **do not** have star formation or radio AGN, but have central entropies below the conduction stabilization limit of $K_0 = 20$ keV cm^2. Henceforth I refer to all objects in my proposed sample as "clusters", but in strict terms the sample is a mix of large groups, poor clusters, and rich clusters. There is the added curiosity that none of these clusters exhibit signs of mergers or dramatic AGN feedback (bubbles or cavities) which might explain their current physical state (the exception being Abell 133 which has a cool "tongue" and radio relic/ghost whose origin is not clear [3]). General properties of my proposed sample are listed in Table 4.

My proposition is that these clusters are in the final stages of low entropy gas condensation in the core which ultimately feeds an AGN outburst cycle. This is a very important stage in the life-cycle of the most massive galaxies in the Universe, and performing an observational "book-keeping" of all the low entropy gas should yield insight into how massive galaxy formation is ultimately truncated via AGN feedback. **As a IPM fellow, I propose to conduct a multiwavelength (X-ray, UV, IR, radio) observational campaign on this peculiar class of galaxy clusters/groups, which have $K_0 \leq 20$ keV cm^2 and either no radio emission or no star formation, in an effort to understand how AGN are fueled, how stars form in the most massive galaxies in the Universe, and to further develop a robust model for coupling the ICM to AGN feedback.** This work will characterize the gas environments of low entropy systems which have thus far been under-studied, and will hopefully yield new constraints on the properties of gas accreting onto the SMBH in the BCG of these systems. Additionally this project will address the hypothesis that conduction plays a crucial role in setting the entropy scale below which star formation occurs, and it will also involve better understanding how AGN feedback energy is dissipated into the ICM.

2 Observations

Multi-phase gas can only be properly accounted for by observing across multiple wavelength regimes. The coldest gas will be brightest in the Far-IR while the hottest gas has already been observed in the X-ray (the impetus for this proposal). As reference, Table 4 lists data which currently resides in publicly accessible archives and will serve to streamline this project.

2.1 X-ray

While high resolution X-ray spectra of cool core clusters have disproved the presence of massive quantities of gas expected in classical cooling flow models ([4]), they have also proven it is possible to detect the heavy element recombination lines of species such as FeXVII and OVIII. These are an important diagnostic for calculating the true mass of gas cooling out of the ICM and into a BCG. For my proposed project I will utilize the RGS instruments on-board *XMM-Newton* to collect high resolution spectra of the cores of my sample. To a lesser degree, *Chandra*'s HETG and LETG instruments will be utilized for cross-calibration purposes. As part of my thesis I have already analyzed the *Chandra* X-ray data for all these clusters, which resulted in temperature, density, entropy, pressure, and mass analysis. The *XMM-Newton* archive will also be utilized to cross-calibrate these results.

Only three clusters require new *XMM* observations: Abell 1204, Abell 2107, and Abell 2556. All of these objects are very luminous ($L_X > 10^{44}$), cool ($T_X < 4$ keV), and relatively nearby ($z < 0.18$) making them ideal candidates for an *XMM* observing proposal. There is excellent scientific justification for observing these clusters, and it is reasonable to believe I will be awarded observing time.

2.2 Ultraviolet and Optical

As an additional constraint on the gas cooling rate, data from *XMM-Newton*'s Optical Monitor will be utilized. This data will be used to calculate star formation rates (SFRs) which will compliment and further constrain cooling rates calculated from RGS/HETG/LETG X-ray spectra and X-ray imaging spectroscopy of *Chandra*. The research group I'm presently working with has already utilized this technique of calculating SFRs from UV excess for 2A 0335+096 ([5]).

2.3 Infrared

Not all UV indicators are unbiased in the estimation of SFRs ([6]) because ionizing radiation can be reprocessed by dust enshrouding star forming regions. This is where utilization of *Spitzer* MIPS and IRAC data will provide an additional, tighter constraint on calculating SFRs and fully accounting for the fate of the cool gas condensing in these low entropy systems. Far-IR photometry will also be useful in determining if a heavily dust obscured AGN is present in systems which no radio AGN was previously detected. Removal of AGN contamination will also be important for accurate determination of SFRs using IR data. The data presently available in the *Spitzer* archive does not provide full-coverage of my sample, but the observations I am suggesting in the Mid-IR do not require the use of cryogen. Thus it is reasonable to believe submission of an observing proposal of $\sim 10 - 12$ hrs. in next year's *Spitzer* AOR cycle has a good chance of being accepted.

2.4 Radio

Analysis of radio data is not predicated upon acceptance of observing time as all the data needed already resides in the VLA archives. For the BCGs which do exhibit radio AGN activity it will be important to reanalyze VLA FIRST or SUMMS data to calculate the energetics of the outflows from the AGN. If conduction is an important mechanism in distributing heat throughout a cool core, then one should also expect AGN kinetic energy to preferentially interact with low density gas and leaving high density gas (in which star formation is most likely to occur) intact. This effect has already been observed in a few cluster cores, but for very powerful AGN outbursts and in BCGs which are not currently experiencing star formation. Uplifting of low entropy gas by an AGN will also need to be investigated as such an effect can potentially skew the total cooling mass too high. I have only listed VLA FIRST high resolution observations which are publicly available in Table 4, but radio data does exist for all my sources, it will need to be acquired through personal request.

3 Analysis: Star Formation Rates and Accounting for Cool Gas

This project is an attempt to directly combine model independent measurements for the majority of cooling gas in the cores of low entropy clusters and characterize the environments in which star formation and AGN feedback *are initiated*. The project I am proposing can be summarized as an attempt to construct the broadest wavelength spectral energy distribution (SED) possible for a sample of extremely interesting cluster BCGs; this is a book-keeping project which will be useful for making a better framework of understanding what happens to cool gas just before and just after an AGN feedback cycle starts.

To constrain the star formation rates in the BCGs of my proposed sample clusters I have chosen a multi-pronged attack. The first task is to calculate X-ray cooling rates for the cluster core from the temperature and density distributions of the ICM. This does not require much effort as I have already done this for my thesis. The X-ray cooling rate establishes the expected amount of gas which will be condensing onto the BCG. Recall, these systems have been chosen because they are dramatically different than their well-heated brethren: low entropy with no radio AGN or no star formation. All three of which are indicators that the cluster is nearing or long removed ($t \geq 1$ Gyr) from the last major heating event.

An additional robust constraint on the properties of the cooling gas will be calculated using the high resolution spectra from RGS. The relative strengths of lines from heavy elements species such as Fe, O, Mg, Ne, and Si will be used to calculate cooling rates and also will serve as a temperature diagnostic for gas which is not spectroscopically resolved by EPIC/MOS and ACIS. Of course these emission lines will not be present with the strengths classic cooling flow models predict, but this is precisely the physical characteristic I am proposing to study.

Complimentary Mid/Far-IR data from *Spitzer* and UV data from *XMM*-OM will also be used to calculate cooling rates. The emission lines from polycyclic aromatic hydrocarbons (PAHs) longward of $\sim 2\mu$ are very useful for detecting dusty starbursts which would otherwise be missed. For the starlight which is not being reprocessed by dust, it can be directly observed in the near-UV and will show up as a luminosity excess. Assuming an IMF and using the L_{UVW1}-L_J relation of [7] (which is founded upon archival *XMM*-OM data) any net UV excess will be used to calculate star formation rates.

Taking all these constraints together will provide a stringent accounting of the state of the lowest entropy gas in these clusters. Taking this sample as a distinctly unique set of clusters and comparing them against other well studied BCGs and cluster cores should reveal if they are different in some fundamental way:

1. Do these clusters truly have cores with fewer stars?
2. Is the ionization state of the ICM in these cluster cores different than typical cool core clusters?
3. Are the effects of conduction glaringly lacking?
4. Is there any evidence for very young dust obscured AGN?
5. Do the gas kinematics suggest bulk motions which are atypical of other cool core clusters?

The answer to these questions are interesting for several reasons. If these cluster cores aren't different from other cool core clusters, meaning we find more stars than are indicated by Hα emission or AGN which aren't radio-loud, then the standard feedback framework is intact. I will be able to slot these clusters into the expected feedback life-cycle. But, what if these clusters have cores that are different from other cool core clusters. One must ask, "what the heck *is* going on?" Why aren't there stars and/or AGN? The standard framework of cluster feedback has a glaring hole in explaining this class of object and a good opportunity to plug that hole will have presented itself.

I can only conjecture at the moment. Imagine an overdense gas parcel buried in a very low entropy medium. As the gas parcel sinks it will reach a region of higher density, stop, and then buoyantly rise. Reproducing this process over an ≈ 10 kpc region should result in all the overdense gas parcels being washed out while the overall entropy of the region continues to lower. The result would be a low entropy core with no overdense regions which could produce stars or gas streams which could reach the SMBH and initiate AGN activity. But is this process stable? Does it require large magnetic suppression of conduction? I'm not sure at the moment, this idea requires more thought.

A logical next step will be in the utilization of radio data to understand the kinematics of the radio AGN (for sources which have them). Within this sample of peculiar clusters should arise another dichotomy- clusters with AGN and clusters without. The star formation rates and cooling rates should be different between these two classes of cluster. This will be related to the plasma outflows of the AGN and may also be related to the weak shocking of the ICM as the jets supersonically move through the dense cluster core environment. An additional exciting use for the radio data will be to "radio date" the AGN in an effort to assign an age for these sources. Several diagnostics will be useful: 1) dynamic age – the age inferred from kinematics of the source (i.e. distance of jets/lobes from nuclear source); 2) synchrotron age – the age inferred from the break frequency of the radio spectrum (presuming no in situ re-acceleration of the jet outflow). Ages of the radio sources will be a very interesting piece of information as it relates directly to the timescales of ICM condensation and feedback energy thermalization.

4 Benefits to IPM Science and Conclusion

This proposal seeks to address many outstanding issues of the feedback regulated cooling in the cores of clusters. All of the questions I've raised in this proposal relate directly to research currently underway at OSU/IPM.

How truncation/downsizing of the massive end of the galaxy luminosity function (GLF) proceeds is not well constrained from observation. However, cosmological simulations which include cooling and feedback are beginning to generate gas distributions which agree with observation ([8]). These simulations also have GLFs which have the appropriate density of massive galaxies and have cluster BCGs which are blue and not red ([9]).

But the successes of models including AGN feedback have also served to highlight the failings of these models observationally. Specifically, we do not currently understand how feedback energy is thermalized within the ICM and most importantly we do not understand how AGN are fueled via cooling from the ICM. As I presented in the introduction, there is good observational and theoretical reason to believe conduction is the answer to both these problems. But in the context of conduction being the solution we will need to account for the peculiar class of clusters which I have presented in this proposal which have low central entropy, no radio AGN (radio being the favored mode of energy transport), and/or no star formation (as inferred from Hα measurements). IPM has an established stake in all these areas of research and will benefit greatly from endorsing me as a fellow to further study them.

The research groups at OSU/IPM have an established reputation for use of *XMM-Newton* which will only serve to make my proposed project all the more fruitful. Specifically, I have not touched on the implications of star formation on metal enrichment in the cores of these clusters, turbulent mixing of the ICM from AGN, and the ICM magnetic fields and their role in shaping the interaction of the AGN with the ICM. All of these topics have been, or are currently, under study by someone at IPM. Many other archival projects could be produced from this proposal by expanding the scope to include the above mentioned topics.

Along with this proposal are also many other topics which could potentially be studied. For example, do AGN blown bubbles contain a very low density non-relativistic thermal plasma or are they truly voids in the ICM (potentially an SZ experiment)? Maybe bubbles contain cosmic rays, a possibility which will make for an interesting GLAST project. How do bubbles rise to distances $\geq$ 100 kpc without being shredded by instabilities? The answer to this question will likely entail better understanding of ICM $\vec{B}$ fields, with their origin being either from preheating, AGN deposition, or a combination of both.

In conclusion, the class of peculiar galaxy clusters I have presented warrant extensive study in their own right, but a uniform, systematic study of these objects will have broad implications for better understanding AGN feedback and star formation in the most massive galaxies in the Universe.

General Properties of Cluster/Group Sample

Name	RA	Dec	z	T_X	K_0	$L_{bol.}$	$L_{H\alpha}$	L_{Radio}
—	hr:min:sec	° :′:″	—	keV	keV cm^2	10^{44} cgs	10^{39} cgs	10^{39} cgs
Abell 133	01:02:41.756	-21:52:49.79	0.0558	3.71	17.26	6.46	6.00	<2.03
Abell 1204	11:13:20.419	+17:35:38.45	0.1706	3.63	15.31	3.92	58.6	<22.2
EXO 0422-086$^{(g)}$	04:25:51.271	-08:33:36.42	0.0397	3.41	13.77	0.65	<0.10	45.2
Abell 2556	23:13:01.413	-21:38:04.47	0.0862	3.57	12.38	1.43	planned	<5.07
Abell 2107	15:39:39.113	+21:46:57.66	0.0411	3.82	11.11	3.02	<1.65	<0.79
Abell 2029	15:10:56.163	+05:44:40.89	0.0765	8.20	10.50	13.9	<5.91	822
AWM7$^{(pc)}$	02:54:27.631	+41:34:47.07	0.0172	3.71	10.21	4.07	planned	<0.18
MKW4$^{(g)}$	12:04:27.218	+01:53:42.79	0.0198	2.16	6.86	0.46	planned	<0.24
ESO 5520200$^{(g)}$	04:54:52.318	18:06:56.52	0.0314	2.34	5.89	1.40	planned	<0.62
MS J1157.3+5531	11:59:52.295	+55:32:05.61	0.0810	3.28	5.54	0.12	planned	<4.44
Abell 2151$^{(pc)}$	16:04:35.887	+17:43:17.36	0.0366	2.90	4.27	1.41	<1.30	0.59
RBS 533$^{(pc)}$	04:19:38.111	+02:24:35.62	0.0123	1.29	2.56	0.17	<0.14	0.61

Notes: Clusters are ordered by decreasing K_0; (g) denotes a group; (pc) denotes a poor cluster. Clusters without Hα are scheduled to be observed using the SOAR Optical Imager (SOI) which is on MSU's SOAR Telescope in Cerro Pachón, Chile.

Exisiting Archival Data

Name	X-ray	Inst.	Grating	Inst.	UV	Inst.	IR	Inst.	Radio	Inst.
Abell 133	Y	*XMM*	Y	RGS	Y	*XMM*-OM	N	——	Y	priv.
Abell 1204	N	—	N	—	N	——	Y	*Spitzer*	Y	*VLA*
EXO 0422-086	Y	*XMM*	Y	RGS	Y	*XMM*-OM	N	——	Y	priv.
Abell 2556	N	—	N	—	N	——	N	——	Y	priv.
Abell 2107	N	—	N	—	N	——	N	——	Y	priv.
Abell 2029	Y	*XMM*	Y	RGS	Y	*XMM*-OM	Y	*Spitzer*	Y	*VLA*
AWM7	Y	*XMM*	Y	RGS	Y	*XMM*-OM	N	——	Y	priv.
MKW4	Y	*XMM*	Y	RGS	Y	*XMM*-OM	Y	*Spitzer*	Y	priv.
ESO 5520200	Y	*XMM*	Y	RGS	Y	*XMM*-OM	N	——	Y	priv.
MS J1157.3+5531	Y	*XMM*	Y	RGS	Y	*XMM*-OM	N	——	Y	priv.
Abell 2151	Y	*XMM*	Y	RGS	Y	*XMM*-OM	Y	*Spitzer*	Y	*VLA*
RBS 533	Y	*XMM*	Y	RGS	Y	*XMM*-OM	N	——	Y	priv.

Notes: All clusters have publically available *Chandra* data.

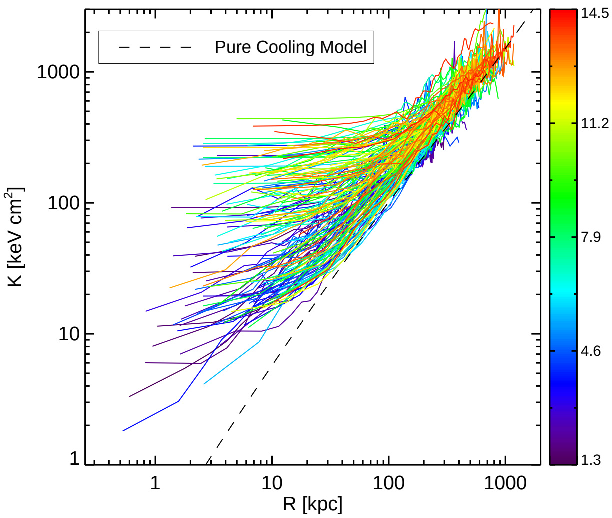

Figure 1: Entropy profiles for 164 clusters of galaxies in my thesis sample. The range of central entropies is consistent with models of episodic AGN heating which regulate the presence of low entropy gas in cluster cores. The so-called "cooling flow" problem does not appear to be a problem any longer.

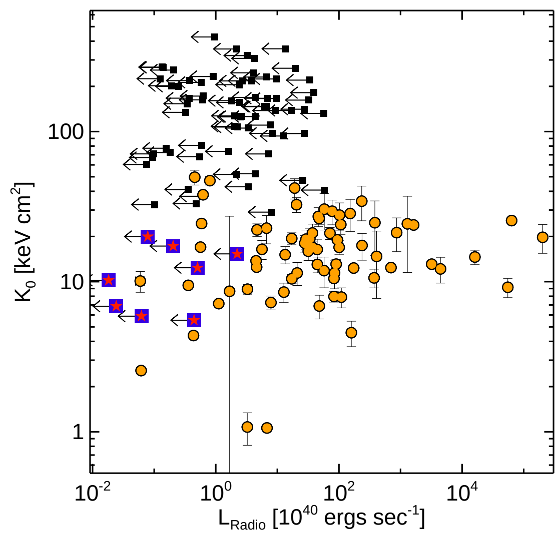

Figure 2: Central entropy derived in my thesis work plotted against radio luminosity calculated using NVSS. Clusters without radio source detections are represented by upper-limits (left pointing arrows). The eight clusters in my sample without radio detections and $K_0 < 20$ are plotted as blue boxes with red stars.

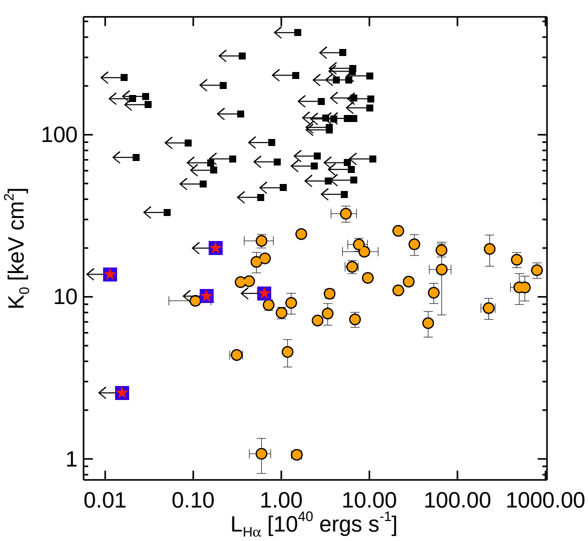

Figure 3: Central entropy derived in my thesis work plotted against Hα luminosity calculated from data in [10]. Clusters without Hα source detections are represented by upper-limits (left pointing arrows). The five clusters in my sample without Hα detections and $K_0 < 20$ are plotted as blue boxes with red stars.

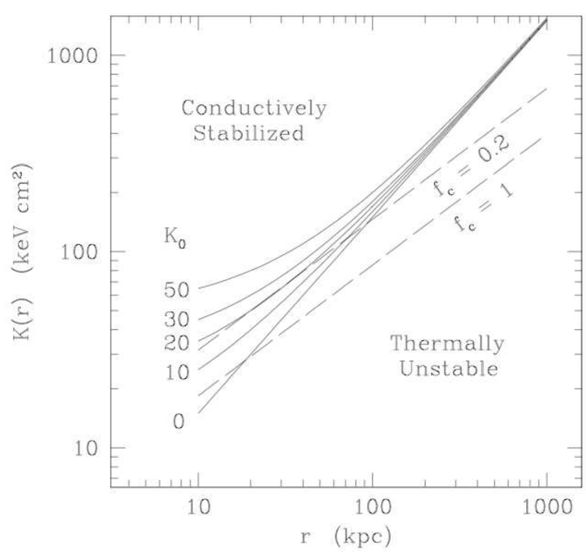

Figure 4: Toy entropy profiles plotted as a function of radius and overlaid with dashed lines representing cooling and conduction equivalence for two suppression factors. Above the dashed lines conduction is effective and condensation cannot occur, the opposite is true below the lines. $K_0 < 20$ keV cm^2 is the break point at which the Field length criterion suggests gas condensation (i.e. star formation and condensation on the SMBH) can proceed. Reproduced courtesy of Dr. G. Mark Voit.

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