Star Formation in the Universe's Largest Galaxies

1. Overview

Current models of galaxy evolution suggest that feedback from active galactic nuclei is needed to explain the high-luminosity cutoff in the galaxy luminosity function. Exactly how an AGN outflow couples with the ambient medium and suppresses star formation remains poorly understood. However, we have recently uncovered an important clue to how that coupling might work. Observations of Hα emission and blue light from the universe's most luminous galaxies, which occupy the centers of galaxy clusters, show that star formation happens only if the minimum specific entropy of the intracluster gas is $\lesssim 20\,\mathrm{keV\,cm^2}$. Our initial theoretical investigations of this entropy limit suggest that it is set by the physics of electron thermal conduction, implying that conduction is critical for channeling AGN energy input toward incipient star-forming regions and limiting the progress of star formation. We are proposing a program of theoretical studies, including numerical simulations, to determine how conduction governs thermal instability and the star-formation rate in brightest cluster galaxies (BGCs), as well as a supporting program of followup observations with the SOAR telescope. The ultimate goal of our program is to develop observational diagnostics of AGN feedback that will enable a more realistic treatment of it in galaxy evolution models.

2. Scientific Motivation

2.1. The Bright Blue Galaxy Problem

What determines the upper limit to the luminosity of a galaxy? This question has received a great deal of attention lately because the answer seems to involve feedback from a galaxy's nucleus, potentially explaining why there is such a tight correlation between the mass of a galaxy's central black hole and the luminosity and velocity dispersion of its spheroidal component. Early treatments of galaxy formation indicated that the upper limit to the galaxy luminosity distribution depends on the cooling time of gas at the halo's virial temperature: objects whose gas cannot cool within a Hubble time cannot form large quantities of stars from that gas (Binney 1977, Rees & Ostriker 1997). Cooling considerations therefore lead to a natural mass scale dividing the largest galaxies, whose gas can cool, from clusters of galaxies, whose gas remains in a hot, extended intracluster medium (ICM).

Those calculations gave upper limits in the right ballpark, but as our understanding of galaxy evolution has matured, the observed cutoff in the galaxy luminosity function has become harder to explain. All serious treatments of galaxy formation these days are based on the foundation of standard ΛCDM cosmology, in which $\approx 16\%$ of the mass is baryonic and structure forms hierarchically. Gas in low-mass halos of dark matter cools quickly, forming stars rapidly, and these halos then merge to form larger, hotter halos in which gas cools more slowly. Semi-analytic models of galaxy formation attempt to compute the star-formation histories of galaxies by tracking this process of merging and cooling, and show that feedback is necessary to account for the observed characteristics of the galaxy luminosity function and its evolution. Without feedback, these models overpredict the number of both low-luminosity and high-luminosity galaxies. Plausible amounts of feedback from supernovae bring the prediction for low-luminosity galaxies into agreement with observations, but getting things right at the high-luminosity end is more difficult—the amount of supernova feedback needed to quench star formation in these systems is implausibly large (e.g. Benson et al. 2003).

Numerical simulations of galaxy formation treat the physics of merging and cooling more realistically, but still do not solve the problem of the high-luminosity cutoff. In current simulations, gas accreting into low-mass systems can radiate energy rapidly enough to remain at $\sim 10^4$ K during the accretion process—a situation that has become known as cold-mode accretion (e.g., Keres et al. 2005). Gas in galaxies growing through cold-mode accretion tends to reside in a cool, rotating, star-forming disk. As halo masses grow, the accretion shocks become stronger, ultimately converting to a hot mode in which accreting gas heats to the virial temperature. Hot-mode accretion sets in when the halo temperature reaches $\sim 10^7$ K and produces a extended halo of hot gas around the galaxy (e.g., Birnboim & Dekel 2003). However, it is still possible for the galaxy to form stars, as long as gas at the center of the system has a cooling time that is less than a Hubble time. In current simulations, cooling by this route is so rapid that the largest galaxies at $z \sim 0$ have luminosities several times larger than the observed cutoff and colors that are much bluer than those of real high-mass galaxies (e.g., Saro et al. 2006). This *bright blue galaxy problem* indicates that we must look beyond supernova feedback to explain the galaxy luminosity function.

2.2. Feedback from Active Galactic Nuclei

A closely related cooling problem has long bedeviled our understanding of galaxy clusters, and X-ray observations strongly suggest that the solution lies with active galactic nuclei. From measurements of the X-ray surface brightness and temperature of intracluster gas, we can determine the cooling time as a function of radius. In roughly half of nearby clusters, the cooling time at $r \lesssim 100$ kpc is less than a Hubble time, implying that gas at the center of the cluster must cool and condense, if there is no feedback to offset cooling. However, observations show that the star-formation rates in these systems are at most 1% to 10% of the expected gas condensation rate. Furthermore, X-ray spectroscopy of these systems shows that the the bulk of the central gas remains suspended at temperatures $\gtrsim 1/3$ of the virial temperature (Peterson & Fabian 2006).

High-resolution imaging with *Chandra* has revealed that many clusters with short central cooling times also have cavities in their ICM that coincide with radio-emitting plasma outflows from the active nucleus in the central galaxy. One can estimate the energy output required to create such a cavity from its volume, the pressure of the surrounding gas, and the buoyancy timescale of the cavity in the intracluster medium. In many cases the energy output of the central AGN is similar to the X-ray cooling rate of the central gas—a strong piece of circumstantial evidence in favor of AGN feedback as the mechanism that limits cooling and star formation in high-mass halos (Birzan et al. 2004, McNamara & Nulsen 2007). Not all clusters with short central cooling times have obvious cavities, but that finding can be understood if AGN heating is episodic.

Despite this circumstantial evidence, it has been difficult to understand how AGN feedback works in detail. The active nucleus itself is extremely small (< 1 pc) compared with the region it needs to heat (~ 100 kpc), and it is unclear how the energy of a bipolar AGN outflow becomes distributed over the entire spherical volume that needs to be heated. Because this problem is both interesting and important, it has attracted the attention of many simulators, who have explored numerous aspects of the AGN-ICM interaction. Some general results are the following:

- It is possible for AGN feedback to strongly limit the cooling and condensation rates in clusters (e.g., Ruszkowski & Begelman 2002, Brighenti & Mathews 2003, Dalla Vecchia et al. 2004, Omma et al. 2004, Sijacki & Springel 2006)
- Much of the AGN energy is thought to be transferred to the ICM by buoyantly rising cavities; however, hydrodynamic instabilities tend to shred these cavities before they rise very far, unless magnetic fields somehow stabilize them (e.g., Robinson et al. 2004)
- Bipolar flows have trouble depositing enough heat in the equatorial direction, possibly leading to a cooling circulation flow (Vernaleo & Reynolds 2006)

Inspired by these developments, the purveyors of semi-analytic models have incorporated schematic implementations of AGN feedback and find that "radio-mode" feedback is a plausible explanation for both the observed cutoff in the galaxy luminosity function and the fact that the largest galaxies in the universe are red, not blue (Croton et al. 2006, Bower et al. 2006). To match the observations, radio-mode feedback must occur preferentially in high-temperature systems and must provide feedback energy without making stars. Its effectiveness is limited to systems experiencing hot-mode accretion because an extended hot galactic atmosphere is necessary to halt and thermalize the energy of the AGN outflow.

However, observations of galaxy clusters with short central cooling times and X-ray cavities show that many of these systems are still managing to form stars, albeit at a reduced rate. The colors of the central galaxies in these clusters are bluer than those without short cooling times, and they host emission-line nebulae powered, at least in part, by hot young stars (see § 3). Radio-mode feedback in these systems may be suppressing star formation, but it is not completely stopping it.

2.3. Entropy Analysis

During the past several years our group has developed entropy analysis into a powerful tool for analyzing the signatures of cooling and feedback in the intracluster medium (see Voit 2005 for a review). Entropy is more illuminating than temperature because the temperature of a gravitating system does not necessarily decrease as it radiates away its thermal energy. Contraction during the process of condensation performs work on cooling gas in a gravitational potential, and the gas near the center of a galaxy cluster is close to hydrostatic equilibrium within a dark-matter potential well. Its temperature and temperature gradient are therefore determined primarily by the depth and shape of the well and only secondarily by cooling and feedback processes. Entropy, on the other hand, depends directly on heat input and radiative losses.

The quantity we use to track entropy is the adiabatic constant $K = Tn^{-2/3}$, essentially the logarithm of the specific entropy. Heat input through feedback raises K, radiative cooling lowers it, but gentle expansion or compression within a potential well does not change it. Furthermore, convection within a relaxed cluster causes its gas to stratify in entropy so that $dK/dr \geq 0$, meaning that the ICM structure of a relaxed cluster is completely determined by the shape of its dark-matter potential well and the distribution of specific entropy in its ICM. In the absence of cooling and feedback, the distribution of entropy as a function of radius should be self-similar, leading to the same ICM structure for clusters of all masses. Simulations show that the baseline entropy profile generated by gravitationally-driven shocks during hierarchical structure formation has a power-law form, $K(r) \propto r^{\alpha}$ with $\alpha \approx 1.1-1.2$, except within about 10% of the virial radius, where the entropy profile flattens somewhat (Voit et al. 2005).

Voit & Bryan (2001) showed that cooling and feedback inevitably conspire to modify this baseline entropy structure. Gas with entropy less than the cooling threshold,

$$K_{\rm c}(T) \approx (135\,{\rm keV\,cm^2})(kT/2\,{\rm keV})^{\beta} \quad , \tag{1}$$

with $\beta = 2/3$ for $T > 2$ keV and $\beta = 0$ for $T < 2$ keV, can radiate away its thermal energy in less than a Hubble time. It must therefore condense, forming stars or fueling an AGN, until either all the low-entropy gas has cooled out of the ICM or feedback has raised the remaining gas above the cooling threshold. Models with similarity breaking at the entropy scale K_c are quite successful at reproducing the observed properties of clusters (Voit et al. 2002), and numerical simulations have shown that including cooling and supernova feedback greatly improves the realism of the resulting galaxy clusters (Borgani et al. 2004, Nagai et al. 2007).

However, the eradication of low-entropy gas from the cores of present-day clusters by cooling and feedback is incomplete. As we have already discussed, the remaining low-entropy gas seems to trigger AGN feedback as it tries to cool, retarding condensation and limiting the star-formation rate. Cosmological simulations have so far been unsuccessful at reproducing the observed properties of this central gas. For example, observations show that these clusters have cool cores with central temperature gradients that rise with radius from 10 to 100 kpc, but cluster simulations with cooling

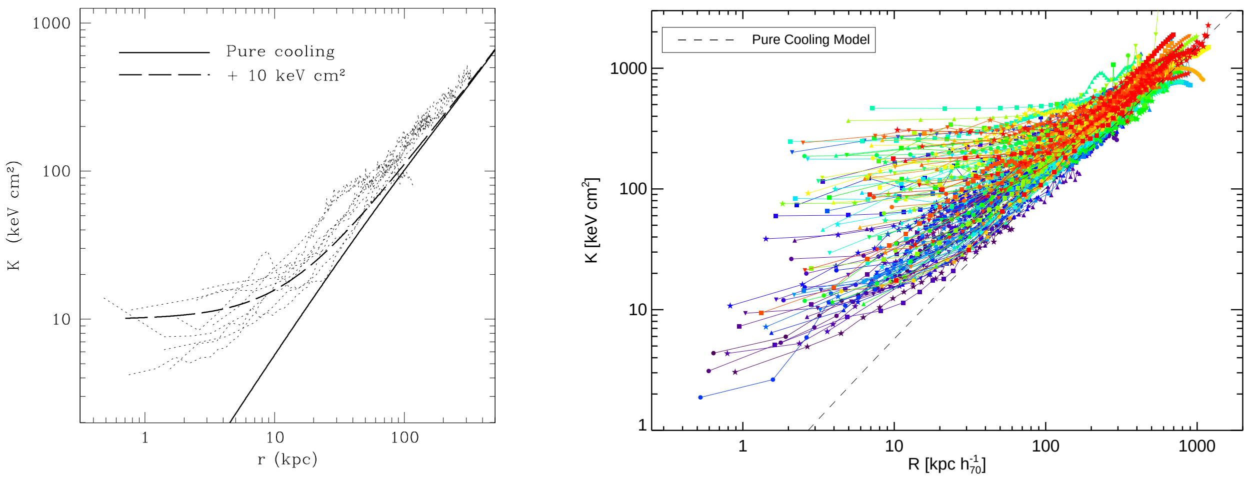

Fig. 1.— ICM entropy profiles observed with *Chandra*. Left panel: Dotted lines show entropy profiles for nine "active clusters" with strong radio emission, X-ray cavities, and/or Hα emission (Voit & Donahue 2005). A solid line shows the "pure cooling" entropy profile for an isolated cluster that has been allowed to cool without feedback for a Hubble time (Voit et al. 2002). The observed entropy profiles are well represented by the pure-cooling profile plus the constant $K_0 = 10\,\mathrm{keV\,cm^2}$ (long-dashed line), which is the entropy boost characteristic of AGN feedback with a power $\sim 10^{45}\,\mathrm{erg\,s^{-1}}$. The similarity of these profiles suggests that self-regulating AGN feedback maintains a quasi-equilibrium state in these cluster cores. Right panel: $K(r)$ for ~ 150 clusters in the *Chandra* archive (K. Cavagnolo Ph.D. thesis). About half of the sample has central entropy $K_0 \lesssim 20\,\mathrm{keV\,cm^2}$, and there is a deficit of clusters with $K_0 \sim 20 - 40\,\mathrm{keV\,cm^2}$. Central entropy values above this level are very difficult to produce with AGN feedback alone and may require mergers.

and supernova feedback tend to produce clusters with hot cores having temperatures that decline from 10 to 100 kpc (Tornatore et al. 2003, Nagai et al. 2007). Clearly, some essential physics is missing from the simulations, which could include AGN feedback as well as the transport processes of conduction and viscosity.

2.4. Entropy and AGN Feedback

Observations of intracluster entropy profiles have provided some important clues to how AGN feedback might operate. Our initial ICM entropy survey included eleven clusters with central cooling times less than a Hubble time. Nine of these clusters showed evidence for feedback in the form of radio emission, X-ray cavities, or Hα emission. In many cases, these "active clusters" displayed all three manifestations of feedback (Donahue et al. 2006). The other two clusters in the survey, the "passive clusters," showed no such evidence for feedback (Donahue et al. 2005).

The left panel of Figure 1 presents central entropy profiles for the nine active clusters. They are all very similar in an unscaled $K(r)$ plot, suggesting that AGN feedback often leads to a well regulated quasi-equilibrium state. A solid line in the plot shows the entropy profile predicted by a "pure cooling" analytical model in which radiative cooling is unopposed by feedback (Voit et al. 2002). It appears to define a limiting lower envelope to the observed profiles, and adding a constant entropy pedestal of $\sim 10\,\mathrm{keV\,cm^2}$ to this limiting profile (long-dashed line) produces a reasonable match to the observations. Voit & Donahue (2005) have shown that this entropy pedestal can be created by a $\sim 10^{45}\,\mathrm{erg\,s^{-1}}$ AGN outburst lasting for $\sim$ 30 Myr. Because ICM gas at an entropy level $\sim 10\,\mathrm{keV\,cm^2}$ can radiate its thermal energy in $\sim 10^8$ years, periodic AGN outbursts on this timescale can maintain the observed quasi-equilibrium structure.

In contrast, the two passive clusters have much higher central entropy values. Fitting the form $K(r) = K_0 + K_{100}(r/100\,\mathrm{kpc})^\alpha$ to the entropy profiles of all eleven systems shows that the passive systems have $K_0 \gtrsim 30\,\mathrm{keV\,cm^2}$, corresponding to a central cooling time $\gtrsim$ 1 Gyr, while the active ones have $K_0 \lesssim 15\,\mathrm{keV\,cm^2}$. All systems converge to $K_{100} \sim 150\,\mathrm{keV\,cm^2}$ and $\alpha \approx 1$ at larger radii. Greater central entropy in the passive systems provides support for the AGN feedback hypothesis in the following sense: If nuclear activity were unrelated to the central entropy of the ICM, then we would expect no correlation between these two quantities. However, if AGN feedback is what stabilizes cooling within the brightest cluster galaxy, then we would expect to see less evidence for feedback in systems with longer central cooling times, as is observed.

We have since expanded our *Chandra* entropy profile survey in order to explore more deeply how the characteristics of feedback depend on central entropy K_0. The right-hand panel of Figure 1 shows our current results for $\sim$ 150 clusters drawn from the *Chandra* archive (K. Cavagnolo, Ph.D. thesis). In this sample, the distribution of central entropy values appears to be roughly bimodal, with a deficit of clusters having $K_0 \sim 20 - 40\,\mathrm{keV\,cm^2}$. The cause of this dichotomy is not yet clear. Voit & Donahue (2005) have shown that AGN outbursts of $\gtrsim 10^{46}\mathrm{erg\,s^{-1}}$ are needed to lift a cluster from a low central-entropy state to $\gtrsim 30\,\mathrm{keV\,cm^2}$. Achieving $\gtrsim 100\,\mathrm{keV\,cm^2}$ therefore seems energetically prohibitive with AGN feedback alone. At least some of the clusters with $\gtrsim 100\,\mathrm{keV\,cm^2}$ are merging systems in which the low-entropy core may have been disrupted, to reform later as the low-entropy gas sinks back to the center of the potential well.

3. Recent Insights

The research we are proposing here is inspired by some recent discoveries about the relationship between the entropy of a cluster's hot gas and star formation in its brightest central galaxy (BCG). Star formation appears to proceed in a BCG when its central entropy is below $K_0 \lesssim 20\,\mathrm{keV\,cm^2}$, even when AGN feedback is present, but is still an order of magnitude below the expected star-formation rate in the absence of feedback. Our hypothesis is that the onset of star formation below this entropy threshold is due to a qualitative change in the ability of conduction to suppress thermal instability in the intracluster medium. Conduction still manages to channel the energy imparted by AGN feedback into the cooling gas, but only reduces the star formation rate without entirely stopping it. If this hypothesis is correct, then conduction is crucial to understanding how AGN feedback suppresses star formation in large galaxies.

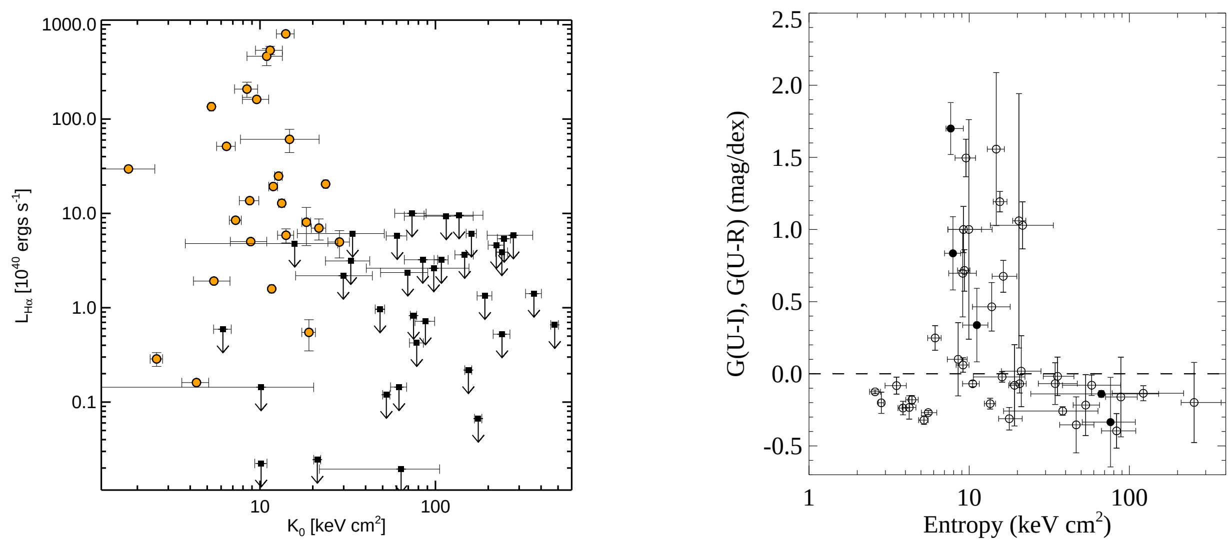

Fig. 2.— Dependence of star-formation tracers in BCGs on central entropy. Left panel: Best-fit central entropy K_0 vs. Hα luminosity (from K. Cavagnolo Ph.D. thesis). Central entropy has been measured with *Chandra*, and $L_{\rm H\alpha}$ values are a heterogeneous set taken from the literature. Notice that Hα emission appears only when $K_0 \lesssim 20\,{\rm keV\,cm^2}$. Right panel: Central entropy vs. BCG color gradient (courtesy of D. Rafferty). Notice that the only BCGs with unusually blue centers are those in clusters with central entropy $\lesssim 20\,{\rm keV\,cm^2}$. Both plots suggest that star formation turns on in BCGs below this central entropy threshold.

3.1. Entropy Threshold for Star Formation

Figure 2 shows how two different tracers of star formation depend on central entropy. The left-hand panel illustrates the dependence of a BCG's Hα emission on K_0, as measured from fits to the radial ICM entropy profiles (Cavagnolo et al., in preparation). Emission-line luminosities in this plot have been taken from the literature and correspond to a variety of apertures—the quantitative values of $L_{\rm H\alpha}$ in this plot are not very meaningful. However, the entropy threshold for having detectable Hα emission is quite clear—it turns on for entropy values $K_0 \lesssim 20\,{\rm keV\,cm^2}$, corresponding to a cooling time $\lesssim$ 300 Myrs. The presence of Hα emission clearly indicates that the intracluster medium can have a multiphase structure below this entropy threshold, with a component at $\sim 10^4$ K in addition to the X-ray emitting component at $> 10^7$ K. At least some of this Hα emission is excited by hot, young stars (Voit & Donahue 1997), but it is also possible for Hα emission to arise from a conductive interface between the X-ray emitting gas and cooler clouds embedded within it (e.g., Sparks et al. 2004).

The right-hand panel (kindly provided by D. Rafferty in advance of publication) plots color gradients in the central galaxy against the central entropy value. Here the central entropy has been measured from a small X-ray aperture $\sim 2-3\,$arcsec at the center of the cluster, and the color gradients have been measured in $U-I$ and $U-B$, with $G(U-I) = d(U-I)/d\log r$ and $G(U-R) = d(U-R)/d\log r$. Again one sees a striking transition. Many galaxies with central entropy below the threshold value $\sim 20\,\mathrm{keV\,cm^2}$ have unusually blue cores, indicating star formation, while none of the galaxies above this threshold have unusual color gradients.

3.2. The Role of Conduction

We suspect that the critical entropy threshold for multiphase gas and star formation in BCGs results from electron thermal conduction. George Field, in his landmark work on thermal instability in the interstellar medium (Field 1965), discovered a critical length scale below which thermal conduction smoothes out temperature inhomogeneities. Multiphase gas and star formation should appear only in systems whose size is greater than this critical length scale, now know as the *Field length*. One can derive the Field length heuristically by considering thermal balance for a cool cloud of radius r embedded in a medium of temperature T. Electron thermal conduction sends energy into the cloud at a rate $\sim r^2\kappa(T)\cdot T/r$, where $\kappa(T) = 6\times10^{-7}T^{5/2}f_c \mathrm{ergs\,s^{-1}K^{-1}cm^{-1}}$ is the Spitzer conduction coefficient and f_c is a suppression factor depending on the magnetic field structure in the medium. Radiative cooling can rid the cloud of energy at a rate $\sim r^3 n^2\Lambda(T)$, where the cooling function $\Lambda(T) \propto T^{1/2}$ for $T > 2$ keV. Cooling and conduction are therefore in approximate balance for systems with a radius of order the Field length,

$$\lambda_{\mathrm{F}} \equiv \left[\frac{T\kappa(t)}{n^2\Lambda(T)}\right]^{1/2} = 4\,\mathrm{kpc}\,\left[\frac{K}{10\mathrm{keV\,cm^2}}\right]^{3/2} f_c^{1/2} \quad . \tag{2}$$

Through a coincidence of scaling, the Field length is a function of entropy alone when free-free emission is the dominant cooling mechanism (Donahue et al. 2005).

Figure 3 illustrates how this criterion translates into the entropy-radius plane. The long-dashed lines give the loci of points for which $\lambda_{\mathrm{F}}(K) = r$, given suppression factors $f_c = 0.2$ and 1. Magnetic suppression of conduction is a complicated and incompletely understood process, but most recent estimates have been in the range $f_c \approx 0.2$-0.3 (Malyshkin 2001, Narayan & Medvedev 2001). Below each line, gas within radius r constitutes a subsystem whose scale exceeds the Field length. Conduction cannot stabilize that gas against cooling, allowing multiphase gas to persist and star formation to proceed. Above each line is the region of stability, in which conduction leads to evaporation and homogeneity.

Solid lines in Figure 3 show schematic intracluster entropy profiles motivated by the data in Figure 1, with $K(r) = K_0 + (150\mathrm{keV\,cm^2})(r/100\mathrm{kpc})$ and $K_0 = 0$, 10, 20, 30, and 50 keV cm^2. Notice that only those profiles with $K_0 \lesssim 20\,\mathrm{keV\,cm^2}$ dip below the threshold for conductive stabilization. In the case of $f_c = 0.2$, the threshold at $r \lesssim 50\,\mathrm{kpc}$ virtually coincides with the profile having $K_0 = 20\,\mathrm{keV\,cm^2}$, strongly suggesting that conduction moderately suppressed by magnetic fields is responsible for the sharp transitions evident in Figure 2.

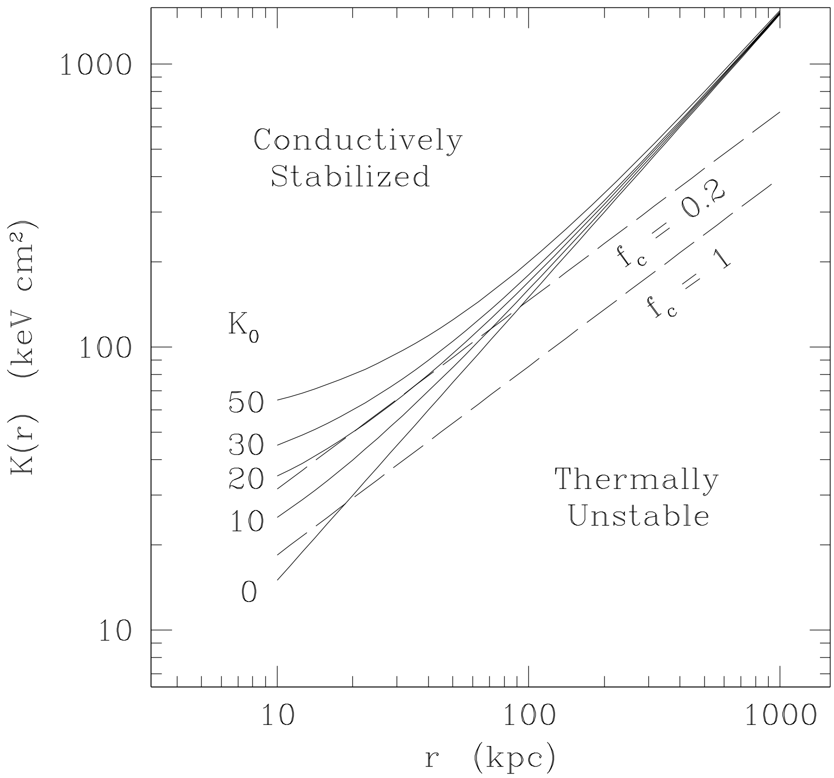

Fig. 3.— Regions of thermal stability in the ICM based on the Field-length criterion. Long-dashed lines show where $\lambda_{\rm F}(K) = r$ for conduction suppression factors $f_c = 0.2$ and 1. Above these lines, conduction is more effective than radiative cooling and causes cooler structures of scale $< r$ to evaporate. Below these lines, radiative cooling is more effective than conduction, allowing thermal instability to proceed. Solid lines show schematic entropy profiles of the form $K(r) = K_0 + (150\,{\rm keV\,cm^2})(r/100\,{\rm kpc})$, inspired by the data in Figure 1. According to the Field-length criterion, thermal instability can proceed and multiphase gas can persist only in systems with $K_0 \lesssim 20\,{\rm keV\,cm^2}$, if $f_c \gtrsim 0.2$. This result potentially explains why Hα emission and excess blue light from star formation are found only in systems with central entropy below this critical value.

4. Proposed Research

These recent results have broad implications for the bright blue galaxy problem and the efficacy of AGN feedback. Energy from AGN outbursts is not deposited homogenously within the cluster core but rather is often preferentially distributed along a bipolar outflow axis. Vernaleo & Reynolds (2006) have shown that AGN feedback in simulations without conduction is ineffective in suppressing cooling and star formation away from the outflow axis. Furthermore, kinetic AGN feedback acts most directly on the lower-density component of the surrounding medium, leaving higher-density, potentially star-forming gas in its wake. Conduction can solve these problem by transmit feedback energy to the equatorial regions and to any other spot where the gas temperature grows unusually low, but its effectiveness depends on the entropy structure of the hot component. Studies of thermal instability and star formation in BCGs are therefore crucial to understanding the linkage between the radio mode of AGN feedback and star formation in the galaxies that populate the upper end of the galaxy luminosity function.

We are proposing a set of investigations, primarily theoretical but with some observational support from the SOAR telescope, to clarify the coupling between AGN feedback, thermal conduction, and star formation in the universe's largest galaxies. Our theoretical studies will focus first on the thermal stability of gas in BCGs, in order to determine the conditions under which a multiphase medium and star formation are possible. They will include both analytical investigations and numerical simulations of thermal instability in the intracluster medium. The simulations will elucidate what is required for conduction to suppress thermal instability, placing the conjecture outlined in Figure 3 on a firmer quantitative foundation and enabling observational testing of it. For cases in which multiphase structure is persistent, we will also calculate the expected line-emission signatures for comparison with observations. In parallel with our theoretical work, we will be using our share of MSU's time on the SOAR telescope to obtain detailed URI and Hα imaging of nearby BCGs, along with emission-line spectroscopy, so that we can test our theoretical models. The following paragraphs outline these plans in more detail.

4.1. Conduction and ICM Stability

Theoretical studies of conduction in the intracluster medium have a long heritage, focusing mostly on whether conduction can completely suppress condensation, given the temperature and density gradients observed in cluster cores (see Kim & Narayan 2003 and references therein). *Chandra* observations have shown that at least some clusters have central gas densities so large (i.e., so low in entropy) that conduction cannot compensate for radiative cooling, even when conduction is unsuppressed (Zakamska & Narayan 2003, Voigt & Fabian 2004). Furthermore, numerical simulations of cluster formation that include conduction and supernova feedback fail to suppress star formation in the BCG (Dolag et al. 2004), demonstrating that additional feedback is required. Our stability studies therefore have a different focus than previous ones—we are primarily interested in how conduction regulates the transition between a single-phase medium and a multiphase medium in a BCG.

4.1.1. Stability Analyses

We will use analytical methods to explore how the thermal stability of gas in a BCG potential depends on its entropy distribution. Such gas is known to be globally unstable to cooling (Kim & Narayan 2003, Soker 2003), but we will investigate the conditions under which it can cool inhomogeously, leading to the multiphase structure necessary for star formation. The presence of a gravitational potential means that we cannot directly apply Field's stability criterion because of buoyancy effects. Condensing perturbations must still have a wavelength greater than the Field length. However, the transition to an inhomogeneous phase structure depends critically on the slope of the entropy gradient because condensing gas clumps that lose entropy via radiative cooling will start to sink, and if they descend to levels of equivalent entropy as quickly as they cool, then the gas will remain homogenous (Malagoli, Rosner, & Bodo 1987, White & Sarazin 1987).[1] We will therefore adapt the thermal stability analyses of Balbus & Soker (1989) and Kim & Narayan (2003), which account for buoyancy effects, to our observations of entropy profiles in BCGs.

4.1.2. Numerical Simulations

We will explore the thermal stability of ICM gas in the non-linear regime using the public-domain *ENZO* code for cosmological hydrodynamics, adapted to include thermal conduction with a variable suppression factor. *ENZO* is an adaptive mesh refinement code well suited to condensation problems that require many orders of magnitude in dynamic range. The P.I. is already familiar with *ENZO* through his collaborative work with the code's author, Greg Bryan.

Several different computations are of interest. We will first follow up our analytical stability analyses to determine the conditions under which non-linear thermal instability can lead to multiphase ICM structure in the core of a galaxy cluster. However, it is possible that the Hα and star-forming gas observed in BCGs comes not from condensation but rather from stripping of cool interstellar gas from other galaxies. In that case, multiphase structure becomes a question of survival, and we will use *ENZO* to determine the conditions under which cold, stripped clouds can survive in a conductive ICM, which we expect will be determined by the Field length in the hot medium.

The next step will be to explore the coupling between conduction and AGN feedback. One feature of galaxy clusters that remains unexplained is the distinct separation between those with cool, low-entropy cores and those with isothermal, high-entropy cores, roughly corresponding to the deficit of clusters in Figure 1 with $K_0 \sim 20 - 40\,\mathrm{keV\,cm^2}$. This separation looks less distinct in central entropy than in central temperature because of the large range in K_0 among the high-entropy clusters. Numerical simulations with only radiative cooling and supernova feedback tend to produce clusters that remain in the low-K_0 state, and extreme AGN outbursts are needed to raise K_0 to $\sim 30\,\mathrm{keV\,cm^2}$ (Voit & Donahue 2005). In the absence of conduction, radiative cooling will return these clusters to a low-entropy state in ~ 1 Gyr (Donahue et al. 2005). Even mergers are surprisingly ineffective at permanently boosting the central entropy of the ICM (Poole et al. 2006). They can temporarily disrupt gas in the core but do not boost its entropy by a large factor.

[1]This mechanism might account for a curious feature in the right-hand panel of Figure 2, namely that the systems with lowest central entropy do not appear to be forming stars. That could be because their entropy gradients are too steep, in which case buoyancy effects can force cooling to be homogenous. If that is the case, then a modest AGN outburst might actually *induce* a limited amount of star formation by flattening the central entropy gradient.

Thus, it eventually sinks back into the cluster core, restoring the original low-entropy state.

Coupling between conduction and AGN feedback can potentially explain the large number of clusters in the high-K_0 state. If a powerful AGN outburst can raise K_0 into the conductively stabilized regime, then the cluster cannot return to a low-K_0 state, even if its cooling time is less than a Hubble time. Subsequent merger shocks can then be much more effective at further boosting K_0, since the core has a lower gas density. We will explore the efficacy of this two-step process using *ENZO* simulations, first with idealized mergers and then with cosmological initial conditions, to see whether it can account for the observed distribution of K_0 among the high-entropy clusters.

4.1.3. Line-Emission Signatures

Many of the points in the left-hand panel of Figure 2 represent clusters hosting well-known Hα nebulae whose energy source continues to be mysterious. At least some of the emission-line luminosity is powered by hot, young stars, but stellar photoionization alone cannot account for all of the observed line ratios, requiring an additional heat source whose flux is similar to the product of energy density and sound speed in the hot medium (Voit & Donahue 1997). In addition, filaments of Hα emission have been observed at large distances from any of the detectable young stars.

Conduction is a plausible source for the extra heat (e.g. Sparks et al. 2004), and we can test this possibility by building on our simulations. For each realization of inhomogeneous ICM conditions, we can compute the 3-D temperature structure and the total surface area of interfaces between hot and cool (10^4 K) components. Using the *CLOUDY* code (Ferland et al. 1998), we can then compute the line-emission signatures expected from conductive interfaces.

Because the interfaces between the observed Hα nebulosity and the X-ray gas are sometimes observed to be very sharp, we will also investigate the line-emission signatures expected when some of the hot electrons from the ambient medium penetrate directly into the cooler gas and deposit their energy there. In that case, the electron energy distribution in the nebula can be non-Maxwellian, with a high-energy tail. We will compute how the line-emission signature changes in that case and compare it with emission-line observations of these nebulae.

4.2. Observations of the Star-Formation Transition

4.2.1. SOAR Imaging of Star Formation and Hα

The observational part of our program will take advantage of our share of MSU's time on the SOAR telescope. With the SOAR Optical Imager (SOI), we will obtain multicolor and Hα imaging of BGCs from Ken Cavagnolo's thesis sample of galaxy clusters, for which we already have extensive information about intracluster entropy from *Chandra*. Our goal will be to obtain UBI

and emission-line images of ~ 30 nearby BCGs within clusters having a range of entropy profiles, to explore in detail how star formation and multiphase gas correlate with the entropy structure of the host cluster. The SOAR imaging will allow us to determine the radial extent of star formation and Hα nebulosity for comparison with the X-ray imaging and numerical modeling, enabling direct tests of the conduction-limited star formation hypothesis. We anticipate devoting 10 full nights over the three-year duration of our program to this imaging project.

In parallel, we will use the Goodman spectrograph on SOAR to obtain long-slit emission-line spectroscopy of the nebulae in these systems. These observations will be compared with the predictions of our emission-line modeling of conductive interfaces in a multiphase ICM. We will pay particular attention to how the emission-line ratios change as a function of distance from obvious star-forming regions, to test the hypothesis that conduction is primarily responsible for exciting the line emission far from young stars. Another 10 nights will be devoted to the spectroscopy project.

4.2.2. Complementary Observations

Both the P.I. and Co.I. are investigators in large *Spitzer* collaborations to obtain infrared spectral energy distributions and emission-line spectroscopy of BCGs. Much of the *Spitzer* data are already in hand, and there is a large amount of overlap with the Cavagnolo et al. *Chandra* sample. At least 90 of these clusters will have at least some *Spitzer* archival data before the cryogen runs out. We will incorporate these data into our star-formation analyses. The *Spitzer* data are particularly useful in this regard because they have the potential to reveal star-formation that is shrouded by dust and therefore less obvious in our optical observations.

Another resource we will use to assess star formation in BGCs is the archived data from the optical monitor on *XMM-Newton*, which is actually a UV telescope with wavelength coverage down to 170 nm. Most of the BCGs we would like to study have been observed with this instrument because it collects data during each X-ray cluster observation. Hicks & Mushotzsky (2005) have shown that these data are very useful for measuring star formation rates in BCGs, and combining this UV data with our optical and *Spitzer* data will give us a complete picture of the star-formation rate, starburst age, IMF, and dust obscuration in these galaxies.

4.3. Broader Impacts

- **Student Training.** The graduate student mostly likely to work on this project, Ms. Emily Wang, is currently a first-year student, and as a woman, is a member of an underrepresented group in astronomy. P.I. Voit is currently supervising two other Ph.D. students, David Ventimiglia and Neelam Dhanda, also a woman. During the past four years, he has supervised four undergraduate thesis projects, as well as an undergraduate summer intern, Jovan Hill, who was part of MSU's McNair/SROP fellowship program for minority students. Approximately half of Voit's teaching load at MSU consists of large astronomy courses for non-scientists, and in 2006-7 he reworked MSU astronomy lab course (1000 students per year) to make it more team-oriented and inquiry-driven. Co.-I. Donahue has a similar teaching profile, with two current Ph.D. students and three recent undergraduate theses

- **Public Outreach.** Both the P.I. and Co.-I. are very active in public outreach. In addition to giving many public talks on astronomy at museums around the country, including seven in Michigan, Voit has directed the astronomy events at the Michigan Science Olympiad for the last three years, and is currently working with the LADDERS program at the MSU museum to develop virtual field trips highlighting astronomy for middle-school students using the museum's teleconferencing system. Donahue is also part of the LADDERS development team.

- **Textbook Updates.** The P.I. and Co.-I. are both co-authors of a major textbook for introductory astronomy, *The Cosmic Perspective* . Their active involvement in research will help them to communicate the latest results on galaxy evolution and other topics in future editions of the book.

5. Management Plan

Our research plan proceeds as follows:

- **Year 1.** Analytical work on thermal instability and its dependence on ICM entropy begins. This work will inform the planning of numerical simulations of conduction and the transition to a multiphase medium in the BGC. Later in the year, we should be ready for our initial simulation runs. SOAR observing program commences.

- **Year 2.** Simulations runs continue and analysis of the simulation results begins. After some simulations have been analyzed, we will begin our emission-line modeling project based on those simulations. SOAR observing program continues.

- **Year 3.** In the final year of the program we will focus on detailed comparisons between our observations and our simulations of thermal instability and star formation in BGCs. SOAR observing program concludes.

The responsibilities of each investigator are:

- **Mark Voit.** Overall management of theoretical investigations and strategic goals. Voit developed many of the ideas and models that will be tested by the proposed simulations. He will participate in the analysis of the simulations and will facilitate the comparisons between simulation results and observational data.

- **Megan Donahue.** Guidance of the SOAR observational program. Donahue is a veteran SOAR observer and has extensive experience with emission-line imaging and spectroscopy.

- **Emily Wang (Graduate Student).** Analysis of numerical simulations and observational data. ms. Wang is the graduate student who will be carrying out the bulk of the post-execution analysis of the simulations under the direction of Dr. Voit. and will be conducting and analyzing the SOAR observations under the direction of Dr. Donahue.