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The "entropy floor" is porous – remarks on the coexistence of star formation and kinetic AGN feedback

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Abstract. We discuss the morphology of star forming clouds and filaments in the central ($\lesssim 50$ kpc) regions of 16 low redshift ($z < 0.3$) cool core brightest cluster galaxies (BCGs). The sample spans decades-wide ranges of X-ray mass deposition and star formation rates as well as active galactic nucleus (AGN) mechanical power, encompassing both high and low extremes of the supposed intracluster medium (ICM) cooling and AGN heating feedback cycle. Amid evidence that the gas fueling both star formation and AGN activity has condensed from the hot atmosphere, we present new and archival *Hubble Space Telescope* (*HST*) images of far ultraviolet (FUV) continuum emission directly associated with young stars, acting as a calorimeter for the degree to which the suppression of star formation by AGN mechanical feedback may be spatially or temporally inefficient. We discuss evidence for temporal and possibly cyclical variation in star formation rate, wherein elevated cooling episodes are permitted when AGN feedback is in a low-power state, and vice-versa. Several sources exhibit strong morphological evidence that low levels of star formation can survive and may indeed be triggered by the passage of a propagating radio source. We conclude by discussing the apparent coexistence of feedback and star formation. If AGN mechanical power does establish an "entropy floor", this floor must be porous, or raise and lower as the AGN varies in power.

Keywords. Keyword1, keyword2, keyword3, etc.

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1. Introduction

Many giant elliptical, groups, and clusters of galaxies inhabit an X-ray bright halo of $\gtrsim 10^7$ K plasma whose core radiative lifetime is much shorter than its age. Absent a heating mechanism, simple models predict that the rapid cooling of gas within this ~ 100 kpc "cool core" (CC) should result in a long-lived cascade of multiphase clouds collapsing into the galaxy at its center, fuelling extreme star formation rates ($10^2 - 10^3\ M_\odot\ \mathrm{yr}^{-1}$) amid massive reservoirs ($\sim 10^{12}\ M_\odot$) of cold molecular gas (e.g., review by Fabian 1994). Although brightest cluster galaxies (BCGs) embedded in CC clusters do preferentially harbour these supposed cooling flow mass sinks, the observed star formation rates and cold gas masses are often orders of magnitude below predictions, and high resolution X-ray spectroscopy of the intracluster medium (ICM, e.g., Sarazin 1986) is only consistent with reduced cooling at $\sim 10\%$ of the expected classical rates (e.g., review by Peterson & Fabian 2006).

The mechanical dissipation of active galactic nucleus (AGN) power is now routinely invoked by theorists and observers as a solution to the problem, as the average associated energy budget for groups and clusters is large enough to inhibit or replenish cooling flow radiative losses not only at late epochs (e.g., Bîrzan *et al.* 2004), but perhaps over a significant fraction of cosmic time (e.g., Hlavacek-Larrondo *et al.* 2012). The paradigm

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is motivated by very strong circumstantial evidence, including nearly ubiquitous observations of radio-bright AGN outflows driving shocks and excavating kpc-scale buoyant cavities in the ambient X-ray gas, acting as lower-limit calorimeters to the often extreme ($\lesssim 10^{46}$ ergs sec^{-1}) AGN kinetic energy input (e.g., review by McNamara & Nulsen 2012). Yet amid panoramic supporting evidence (reviewed by Fabian 2012), the physics that govern the spatial distribution and thermal coupling of AGN mechanical energy to the multiphase ($10-10^7$ K) gaseous environment remain poorly understood, and cooling flow alternatives invoking (e.g.) wet mergers, thermal conduction, and evaporation have been a persistent matter of debate (e.g., Sparks *et al.* 2012).

Although often invoked exclusively as a star formation quenching mechanism, observations have long demonstrated that AGN mechanical feedback does not completely offset radiative losses or establish an impermeable "entropy floor", instead permitting residual cooling either at constant low ($\sim 10\%$ classical) rates, (e.g., Tremblay *et al.* 2012a,b), or in elevated episodes as the AGN varies in power (e.g., O'Dea *et al.* 2010; Tremblay 2011). Relative to field galaxies or those in non-cool core clusters, BCGs in cool cores preferentially harbour radio sources and kpc-scale filamentary forbidden and Balmer emission line nebulae amid $10^9 - 10^{11}$ $M_\odot$ repositories of vibrationally excited and cold molecular gas (e.g., Heckman *et al.* 1989; Donahue *et al.* 2000; Edge 2001; Salomé & Combes 2003; Edge *et al.* 2010). Low to moderate levels ($\sim 1- \gtrsim 10 M_\odot$ yr^{-1}) of star formation appear to be ongoing amid these mysteriously dusty (e.g., Rawle *et al.* 2012), PAH-rich (Donahue *et al.* 2011) cold reservoirs on $\lesssim 50$ kpc scales in clumpy and filamentary distributions (e.g., O'Dea *et al.* 2010). If the cold gas fuelling star formation in these systems has indeed condensed from the ambient hot atmosphere, then direct observations of young stars in CC BCGs can be used as a calorimeter for the degree to which the

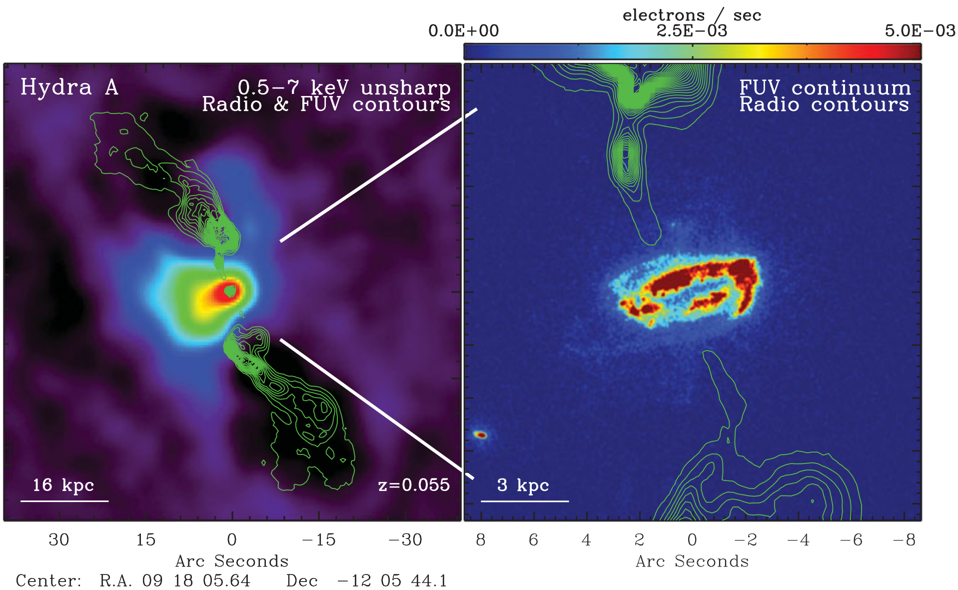

Figure 1. Hydra A (Abell 780) and its central BCG, a canonical illustration of kinetic ("radio–mode") AGN feedback excavating kpc-scale cavities in the ambient X-ray bright intracluster medium, necessary for the inhibition of a catastrophic cooling flow. A *Chandra* X-ray unsharp mask and *HST*/ACS FUV continuum maps are shown in the left and right panels, respectively. The associated radio source 3C 218 is shown in green contours on all panels. Note the ~ 50 kpc-scale X-ray cavities cospatial with the radio lobes. The white box on the X-ray panel marks the FOV the FUV panels. Figure from Tremblay *et al.* 2014b.

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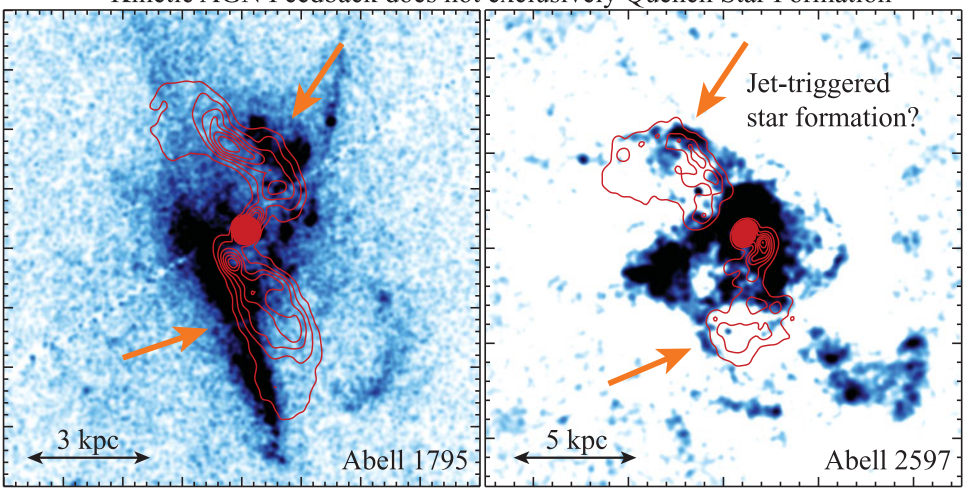
feedback-regulated inhibition of cooling is either spatially or temporally inefficient — a central issue to many of the problems discussed above.

Using new *HST* FUV continuum imaging of young stars in 16 low redshift ($z < 0.3$) CC BCGs, this talk summarized new results that reinforce the long-known (but perhaps under-appreciated) notion that AGN mechanical (radio-mode) feedback is not exclusively a "switch" that shuts off star formation. The data suggest that the coexistence of feedback and star formation may have both a temporal and spatial dependence perhaps coupled to the AGN duty cycle and the directional anisotropy of X-ray cavity and sound wave heating, respectively. These results are summarized as follows, and presented in detail in the forthcoming paper by Tremblay *et al.* (2014b).

• The apparent coexistence of star formation and AGN mechanical feedback may have a temporal dependence. Within our sample, objects with the highest star formation rates tend to possess unresolved and generally faint radio sources, while targets with the lowest star formation rates are associated with more powerful, extended radio sources that are frequently cospatial with kpc-scale X-ray cavities. This result is consistent with the paradigmatic expectation that the radio source is involved in the suppression of star formation. Amid additional evidence that the radio emission is variable (e.g., relic radio sources and multiple sets of buoyantly risen X-ray cavities), this result may also imply that the ICM cooling and AGN heating may be partially cyclical.

• This coexistence of star formation and AGN mechanical feedback may also have a spatial dependence. Star formation avoids X-ray cavities in all applicable cases, and apparently diverts to wrap around the projected edges of cavities in five cases. This may be further evidence for spatially confined channels of uninhibited ICM cooling in regions absent spatially confined AGN and X-ray cavity heating (e.g., A2597). In some cases (e.g., Hydra A), the FUV filaments may have been uplifted or swept aside by the

Kinetic AGN Feedback does not exclusively Quench Star Formation



Figures adapted from Tremblay *et al.* 2012a, 2014b

Figure 2. *HST* FUV continuum imaging of young, massive stars in two nearby cool core brightest cluster galaxies. The star forming filaments strongly spatially align with the radio lobes (shown in red contours), serving as strong evidence for a scenario wherein star formation is triggered by shock-induced cloud collapse as the propagating radio plasma entrains and displaces cold clouds along its boundary layers.

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cavities (or the radio source that excavated them). In other cases (e.g., A1835) the star formation at the base of the cavity may be powered by rapidly cooling hot gas that has been entrained in the buoyant cavity's updraft. Whatever the case, the strong *spatial* anti-correlation between star forming filaments and X-ray cavities in our sample may be evidence for directionally-dependent anisotropy in the efficiency of AGN heating, at least within the innermost ~ 50 kpc.

• One quarter of our sample (A1795, A2597, PKS 0745, and Hydra A) possesses filaments that exhibit strong projected spatial alignment with radio jets and lobes. These may be interpreted either as star forming filaments that have been dynamically entrained or uplifted by the radio source, or they may be evidence for *in situ* star formation arising from (e.g.) shock-induced cloud collapse induced by the propagating jet. The propagating radio source may therefore trigger star formation on small scales while also excavating X-ray cavities and driving sound waves that may ultimately inhibit star formation from the cooling flow. In this way, the seemingly competing roles of a radio source simultaneously creating and preventing star formation may be reconcilable. Nevertheless, the existence of lobe filaments is strong evidence that the kinetic energy feedback of a propagating radio source is, again, not always a switch that shuts off star formation. Anecdotally, we note that both Hydra A jets de-collimate and disrupt into flared lobes directly behind the terminus of lobe filaments, possibly due to significant momentum flux between the jet and ISM at these locales.

Our results augment years of previous work suggesting that, if AGN mechanical feedback does indeed establish an "entropy floor", this floor must be porous, or raise and lower as the AGN varies in power. We suggest that this apparent porosity can play a non-trivial role in the growth of the galaxy's stellar component. It should therefore not be ignored by those invoking AGN mechanical feedback purely as a mechanism to inhibit star formation wherever it is predicted by theory but forbidden by observations.

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