

## X-ray Cavities in Galaxy Groups and Clusters: Central Gas Entropy Excess as Direct Evidence for AGN Feedback

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**Abstract.** Observations of X-ray jets and cavities in clusters of galaxies observed by Chandra are briefly reviewed. A recent study on the excess of central gas entropy, which can be considered as direct evidence for AGN feedback in galaxy groups and clusters is presented. An expanded account of this study has been presented in RAA (Wang *et al.* 2010).

*Key words.* AGN—jets—X-rays—intergalactic medium.

### 1. Introduction

The Chandra X-ray Observatory has a high angular resolution of 0.5 arcsec, similar to that of radio-band observations by the VLA and ATCA. This gives us a chance to study in detail AGN jets and radio lobes at keV energies. As of today, X-ray jets have been found in nearly 100 galaxies on size scales from pc to tens of kpc, with obvious knot and/or hotspot substructures. The possible mechanisms of the X-ray emission is synchrotron radiation of relativistic electrons, powered by the central AGN, and inverse-Compton scattering of relativistic electrons on ambient low-energy photons.

In the X-ray images of galaxies, galaxy groups and clusters, a number of X-ray cavities have been observed. Most of the X-ray cavities are consistent with radio bubbles and/or radio lobes, which indicates that the X-ray cavity is filled with high energy particles. It is estimated that powerful AGN outbursts may repeat every  $10^6$ – $10^8$  yr and release  $10^{58}$ – $10^{62}$  erg every outburst to heat the surrounding gas (see McNamara & Nulsen 2007 for a review). This amount of energy is sufficient to balance gas cooling and heating on group and cluster scales (e.g., Rafferty *et al.* 2006; Birzan *et al.* 2009).

For galaxy groups and clusters, some fundamental astrophysical processes that determine the basic properties of these celestial systems are still poorly understood. For example, the scaling relations between X-ray luminosity, gas temperature, gas entropy and total gravitating mass, which are predicted by the self-similar gravitational collapse scenario (e.g., Kaiser 1986; Navarro *et al.* 1995), are challenged by observed deviations in such a distinct way that non-gravitational heating sources are invoked to dominate the gas heating process in the central  $\simeq 100$  kpc (e.g., Ponman *et al.* 2003; Donahue *et al.* 2006; Sun *et al.* 2009).

The most popular non-gravitational heating source is AGN feedback. However, there also exist problems in this scenario. For example, the absence of X-ray cavities

has been reported in about 40% of cool core systems (e.g., Birzan *et al.* 2009), and only about 10% of quasars are found to host powerful radio jets (e.g., White *et al.* 2007). This indicates that cavity- and jet-related feedbacks might not always operate. In NGC 4051, the observed mass and energy outflow rate due to the AGN activity is 4–5 orders of magnitude below those required for efficient feedback (Mathur *et al.* 2009). Also, Jetha *et al.* (2007) found no significant difference of gas entropy profiles between radio-loud and radio-quiet galaxy groups (see also Sun *et al.* 2009).

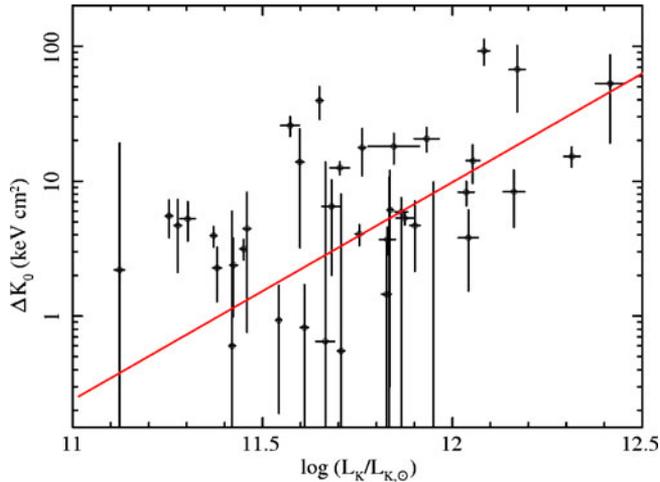
If AGN feedback does dominate the gas heating history in central regions of galaxy groups and clusters, it should be proportional to the central gas entropy excess  $\Delta K$ , i.e.,  $E_{\text{feedback}}^{\text{AGN}} \propto \Delta K$  (Voit & Donahue 2005), where  $\Delta K$  is measured beyond a power-law model that best describes the gas entropy distribution in the intermediate and outer regions. On the other hand, by studying AGN cavities embedded in the X-ray halos of galaxy groups and clusters, Allen *et al.* (2006) found a close relation between the AGN feedback energy  $E_{\text{feedback}}^{\text{AGN}}$  and the Bondi accretion power  $P_{\text{Bondi}} = \eta \dot{M} c^2 \propto M_{\text{BH}}^2$  ( $\eta$  is the mass-to-energy conversion efficiency,  $\dot{M}$  is the accretion rate and  $M_{\text{BH}}$  is the black hole mass), which indicates that the AGN feedback should scale with the SMBH mass as  $E_{\text{feedback}}^{\text{AGN}} \propto M_{\text{BH}}^2$ . And we know that  $M_{\text{BH}}$  is related to the galaxy’s bulge luminosity  $L_{\text{bulge}}$  and thus galaxy’s  $K$ -band luminosity  $L_K$  via  $M_{\text{BH}} \propto L_{\text{bulge}} \propto L_K$  (Marconi & Hunt 2003). Given the above relations, we expect a tight correlation between the central gas entropy excess and the galaxy’s  $K$ -band luminosity, i.e.,  $\Delta K \propto L_K^2$ .

## 2. Central gas entropy excess as direct evidence for AGN feedback in galaxy groups and clusters

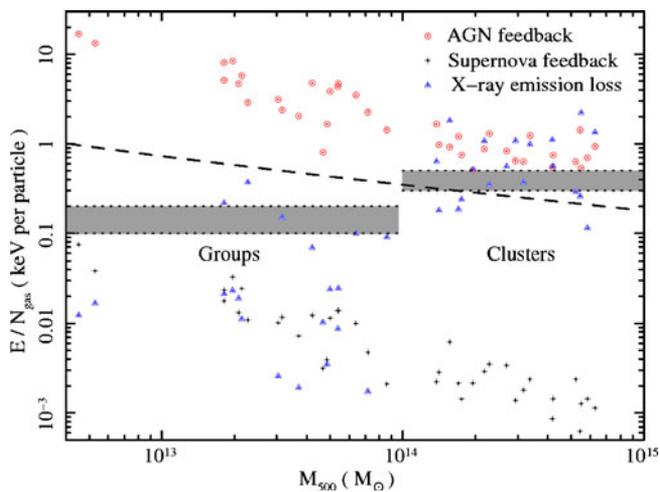
To investigate the interaction between the central AGN and the intergalactic medium (IGM), we select 40 bright, nearby galaxy groups and clusters, which are limited to have only one bright central-dominating galaxy (CDG) and show no significant merger signatures. The central galaxy of the selected systems can be well resolved with the Chandra ACIS. Some basic properties of the sample members are summarized in Wang *et al.* (2010).

After calculating the 3-dimensional azimuthally-averaged radial entropy distribution  $K(R)$  for all of the sample systems, we fit the obtained radial entropy profiles with a power-law expression as  $K(R) = \Delta K_0 + K_{100}(R/100h_{71}^{-1} \text{ kpc})^\alpha$  (Donahue *et al.* 2006), where  $\Delta K_0$  represents the central gas entropy excess beyond the best-fit power-law model for larger radii. We find that in 31 sample systems there exists a significant central ( $R \lesssim 10h_{71}^{-1} \text{ kpc}$ ) gas entropy excess ( $\Delta K_0$ ), which corresponds to  $\simeq 0.1$ – $0.5 \text{ keV}$  per gas particle, beyond the power-law model that best fits the radial entropy profile of outer regions.

In order to investigate the possible relation between the central gas entropy excess and the AGN heating, we show in Fig. 1 the central gas entropy excess  $\Delta K_0$  versus the  $K$ -band luminosity  $L_K$  for the 40 CDGs in our sample (see Wang *et al.* 2010 for details), the latter being tightly associated with the mass of the supermassive black hole hosted in the CDG. The correlation is significant at 90% confidence level, according to the correlation coefficient and Kolmogorov–Smirnov (K–S) test. Using the bisector of ordinary least-squares regression, which is suitable to fit data with large scatter, we fit the  $\log \Delta K_0$ – $\log L_K$  relation with a linear model of  $\log(\Delta K_0) =$



**Figure 1.** Central gas entropy excess  $\Delta K_0$  vs.  $K$ -band luminosity  $L_K$  for the 40 CDGs of our sample (see Fig. 2 in Wang *et al.* 2010). The solid line shows the best-fit model  $\log(\Delta K_0) = -0.8 \pm 0.3 + (1.6 \pm 0.4)[\log(L_K/L_{K,\odot}) - 10.9]$ .



**Figure 2.** Estimated energy feedback to the IGM by AGNs (circles) and supernova explosions (crosses), compared to the average gas energy excess of  $\simeq 0.1$ – $0.2$  and  $\simeq 0.3$ – $0.5$  keV per particle for galaxy groups and clusters (grey belts), respectively, the X-ray radiative loss since  $z = 2$  (triangles), and the energy required to deviate scaling relations from self-similar predictions (dashed line; see Wang *et al.* 2010 for details).

$A + B [\log(L_K/L_{K,\odot}) - 10.9]$ , and obtain  $A = -0.8 \pm 0.3$  and  $B = 1.6 \pm 0.4$  (Fig. 1).

In fact, if an effective mass-to-energy conversion-efficiency of 0.02 is assumed for the accretion process, the cumulative AGN feedback  $E_{\text{feedback}}^{\text{AGN}} \simeq \eta M_{\text{BH}} c^2$  yields the extra heating of  $\simeq 0.5$ – $17.0$  keV per particle (Fig. 2), which is sufficient to explain the central entropy excess. In most cases the AGN contribution can compensate for

the radiative loss of the X-ray gas within the cooling radius ( $\simeq 0.002\text{--}2.2$  keV per particle), and apparently exceeds the energy required to deviate the scaling relations from self-similar predictions ( $\simeq 0.2\text{--}1.0$  keV per particle). In contrast to AGN feedback, the extra heating provided by supernova explosions accounts for  $\simeq 0.01\text{--}0.08$  keV per particle in groups and is almost negligible in clusters. Therefore, the observed correlation between  $\Delta K_0$  and  $L_K$  can be considered as a direct evidence for AGN feedback in galaxy groups and clusters.

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