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AGN heating in complete samples of galaxy clusters

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Abstract. The *Chandra* X-ray Observatory has revealed X-ray cavities in many nearby cooling flow clusters. The cavities trace feedback from the central active galactic nucleus (AGN) on the intracluster medium (ICM), an important ingredient in stabilizing cooling flows and in the process of galaxy formation and evolution. But, the prevalence and duty cycle of such AGN outbursts is not well understood. To this end, we study how the cooling is balanced by the cavity heating for complete samples of clusters (the Brightest 55 clusters of galaxies, hereafter B55, and the HIghest X-ray FLUx Galaxy Cluster Sample, HIFLUGCS). In each sample, we found 35 cooling flow clusters (with $\min(kT/(\Lambda n_e n_H r^2)) \leqslant 5$), of which 22 for B55 and 23 for HIFLUGCS have detected X-ray bubbles in their ICM. Among the remaining systems, all except Ophiuchus could have significant cavity power yet remain undetected in existing images. This implies that the duty cycle of AGN outbursts with significant heating potential in cooling flow clusters is at least 60% and could approach 100%, but deeper data is required to constrain this further.

Key words. Galaxies: clusters: general – X-ray: galaxies: clusters

1. Introduction

Images from *Chandra* show that many clusters have X-ray cavities in their atmospheres (only a small number of cavities were known from previous X-ray observatories, e.g., in M87 and Perseus). The X-ray cavities are interpreted as bubbles created by the central AGN, which rise buoyantly through the ICM from the center of the cluster. They are filled with relativistic particles and magnetic field which emit synchrotron radiation visible at radio wavelengths. The energy that the cavities release in the ICM may be important for balancing cooling (McNamara et al. 2000; Fabian et al. 2000; Blanton et al. 2001) and in the process of galaxy formation and evolution (Croton et al. 2006), but is not clear whether the cavities are always present when heating is required.

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Bîrzan et al. (2004), Dunn & Fabian (2004), Dunn et al. (2005), Rafferty et al. (2006) analyzed samples of cooling flow clusters with visible cavities in their environments. Rafferty et al. (2006) found that 50-80% of the systems with cavities can balance cooling, considering only the enthalpy ($4pV$for $\gamma = 4/3$).

Currently, the cavities are primarily detected by eye. Some of them have rims (e.g., A2052; Blanton et al. 2001) or occupy a large fraction of the emitting volume of the ICM (e.g., MS 0735+7421; McNamara et al. 2005), which make them "clear" cases. However, the detectability of a bubble depends on its location, orientation (Enßlin & Heinz 2002; Brüggen et al. 2009), its angular size and the depth of the observation. As a result, we are likely missing some bubbles in the existing images.

Our goal is to understand the biases and selection effects in the detectability of current X-ray cavity samples, and to place limits on the fraction of systems that can have enough cavity power to balance cooling.

2. A complete sample

In this work we present an analysis of two complete samples: the B55 sample (Edge et al. 1990) and HIFLUGCS (Reiprich & Böhringer 2002). B55 is a 2-10 keV flux limited sample based on the ROSAT data. This sample was studied by Dunn et al. (2006) in order to determine the fraction of cooling flow clusters with bubbles. In order to separate the cooling flow clusters from the non-cooling flow clusters, Dunn et al. (2006) used ROSAT data. They defined a cluster to be a cooling flow cluster if $t_{\rm cool} < 3 \times 10^9$ yr and if it had a large temperature drop, $T_{\rm outer}/T_{\rm center} > 2$. They found that 14 out of 20 cooling flow clusters have clear bubbles. Rossetti & Molendi (2010) used this sample to separate cooling flow from the non-cooling flow clusters and they used the pseudo-entropy ratio as a criterium of separation. The HIFLUGCS is a 0.1-2.4 keV flux limited sample based on ROSAT and ASCA observations at b > 20 degree latitude. This sample was study by Sanderson et al. (2006, 2009) using a temperature ratio in order to separate the cooling flow clusters, Chen et al. (2007) who used a mass deposition rate ratio, and Hudson et al. (2010) who used the central cooling time. The two complete samples they have 42 systems in common.

In order to separate the cooling flow clusters from non-cooling flow clusters we used *Chandra* archive data. We used the same central cooling time cut-off as Dunn et al. (2006) of 3 $\times 10^9$ yr. This cooling time cut-off is in agreement with findings of Rafferty et al. (2008), who found that in systems with visible cavities, the central cooling time is less than $1-3\times10^9$ yr. Since, either the choice of 1×10^9 yr or 3×10^9 yr is not physically motivated, we chose a complementary way to separate the systems that require heating for the others, the cluster thermal stability (Sanders et al. 2009). Using the sample of Rafferty et al. (2006), Voit et al. (2008) found that star formation and H-α (hence cooling) seems to occur if:

$$\min\left(\frac{kT}{\Lambda n_e n_H r^2}\right) \sim \frac{1}{f_c} \leqslant 5, \quad (1)$$

where f_c is the factor by which the magnetic field is suppressing the conductivity below the Spitzer value.

Figure 1 shows the minimum instability criterium versus the monochromatic 1.4 GHz radio luminosity. Radio luminosities are from Mittal et al. (2010) where available, otherwise we calculated them using NVSS fluxes. Also, we collected from the literature information about any merger activity (e.g., sloshing, major mergers etc). The figure shows that systems with a minimum instability ratio above 5 have in general a lower radio luminosity and a higher fraction of mergers.

For this work we selected our sample of systems that require heating based on minimum instability. Based on the cluster stability criterium separation we found that for both B55 and HIFLUGCS 35 systems require heating (they are seven less than the cooling time separation criterium). 22 systems (B55) and respectively 23 systems (HIFLUGCS) out of the 35 cooling flow clusters have cavities: A3391, A1060, A3532, Zw III 54, A496, A2204 (Sanders et al. 2009), Fornax (Shurkin et al. 2008), NGC 4636 (Dunn et al. 2010),

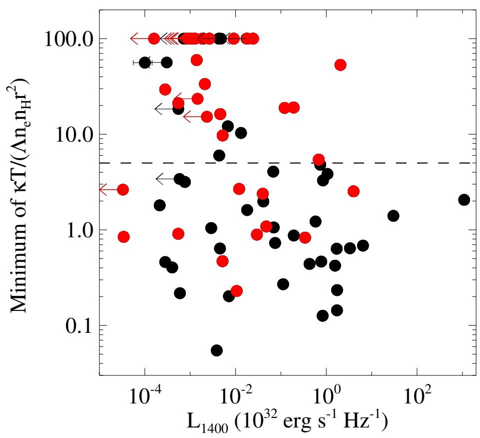

Fig. 1. The minimum instability versus the monochromatic 1.4 GHz radio luminosity. The red color (lighter color) circles denotes the systems which may be in a merger activity (sloshing, minor mergers, major mergers).

NGC 5044 (David et al. 2010) and another 14 systems that were published in Rafferty et al. (2006) sample of clusters with cavities. For the remaining clusters we perform simulations in order to find the location and the size of bubbles that can be present in the image and remain undetected.

3. Simulations

We simulate a 3 dimensional cluster using a double-β profile for the emissivity (derived from the existing archive observations). Then, the cavities are subtracted and by integrating the emissivities along the line of sight, the 2 dimensional surface brightness map is obtained. This map is used as input for the MARX simulator[1] in order to obtain the simulated *Chandra* image.

We use the adiabatic expansion assumption to put limits on the bubble size and location and the buoyancy assumption to calculate the ages. In order to calculate the radius at which the bubbles are injected we assumed: $4pV \sim P_{\rm cav}t \sim L_{\rm X}t$, where p is the central pressure, $L_{\rm X}$ is the bolometric X-ray luminosity and t is the time between the outbursts. We adopted a time between outbursts of 10^8 yr, motivated by the observations of clusters with multiple generation of bubbles, such as Perseus (Fabian et al. 2000). We ran multiple simulations for a cluster, with the locations of the bubbles and the angle in the plane of sky (ϕ) randomized, and with the angle from the line of sight (θ) of 90°. The resulting images are inspected by eye, and for the location at which the bubble becomes invisible (R) we check the age. If the buoyancy age ($t_{\rm buoy}$) is less then 10^8 yr, then such a bubble is physically possible under our assumptions and could then be present in the real cluster and yet remain undetected. If $t_{\rm buoy} > 10^8$ yr, then there should be a new set of bubbles at smaller R which would be detected, so this case is unphysical. Therefore, we repeated the simulation for smaller $P_{\rm cav}$ until $t_{\rm buoy} < 10^8$ yr. This was the case for Ophiuchus and RXCJ 1504.1-0248.

4. Heating versus cooling for complete samples

Figure 2 shows the cavity power (the heating) versus the bolometric X-ray luminosity within the cooling radius (at which $t_{\rm cool} < 7.7\times10^9$ yr). The upper limits in the plot are the cooling flow systems without detected bubbles (13 of them for B55, 12 for HIFLUGCS) for which we performed simulations. For the systems with detected bubbles we used the published values (except A496, A3391, A1060, A3532 and ZW III 54 for which we used our own calculations). From Fig. 2 we can conclude that most systems could have bubbles with enough power to balance cooling and remain undetected in existing images. One system (Ophiuchus) can not have such bubbles, unless they are at $\theta < 30°$. Also, some systems may not have cavities and be in a cooling stage. This may be the case for RXCJ 1504.1-0248, which has very high star formation rates of 140 $M_\odot$ yr^{-1} (Ogrean et al. 2010). Other systems that do not show cavities and which have detected star formation are A1644 (O'Dea et al. 2010) and A3112 (Hicks et al.

[1] see http://www.space.mit.edu/CXC/MARX/

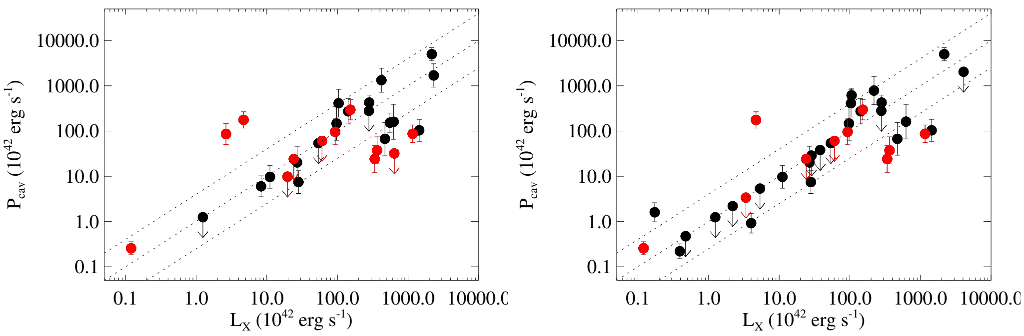

Fig. 2. *Left*: Cavity power versus the bolometric X-ray luminosity for 35 cooling flow clusters selected from the B55 sample. The upper limits are the 13 systems that do not show cavities in their atmospheres, the remaining 22 systems have cavities (see text for details). *Right*: Cavity power versus the bolometric X-ray luminosity for the HIFLUGCS of 35 cooling flow systems, out of which 23 have cavities.

2010). The fraction of systems with detected bubbles ($22 - 23/35 \approx 0.6$) implies a duty cycle in cooling flows of at least 60% (40% of all clusters), lower than the limit of Dunn et al. (2010) that was based on a sample of ellipticals (~ 50%, 9/18). However, with the existing data, one can not exclude the scenario that all cooling flow clusters have bubbles with enough power to balance cooling, implying a duty cycle for such activity of up to 100%. Much further work is needed to improve constraints on the duty cycle of cavity production, such as: adding rims to cavities, investigating different schemes for bubble evolution, quantifying the detection threshold and investigate the detectability of X-ray cavities by comparing with the radio images (Burn 1990; Mittal et al. 2010).

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