Scrutinizing the AGN heating mechanism in galaxy clusters

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Abstract.
We carried out an intensive study of the AGN heating−intracluster medium (ICM) cooling network by comparing various cluster parameters to the integrated radio luminosity of the central AGN, L_R. This study is based on the *HIFLUGCS* sample comprising the 64 X-ray brightest galaxy clusters. Based on the central cooling time, t_{cool}, we classify clusters with $t_{cool} < 1$ Gyr as strong cool-core (SCC) clusters, with 1 Gyr $< t_{cool} < 7.7$ Gyr as weak cool-core (WCC) clusters and with $t_{cool} > 7.7$ Gyr as non-cool-core (NCC) clusters. We find 48 out of 64 clusters contain cluster center radio sources (CCRS). Furthermore, we find that the probability of finding a CCRS increases from 45% to 67% to 100% for NCC, WCC, and SCC clusters, respectively.

We find that L_R in SCC clusters depends strongly on the cluster scale such that more massive clusters harbor more powerful radio AGN. The same trend is observed between L_R and the classical mass deposition rate, $\dot{M}_{classical}$. We also perform correlations of the luminosity for the brightest cluster galaxy, L_{BCG}, in all 64 clusters. Using the near-infrared bulge luminosity-black hole mass relation to convert L_{BCG} to supermassive black hole mass, M_{BH}, we find a weak correlation between M_{BH} and L_R for SCC clusters, although with a few outliers. We find an excellent correlation of L_{BCG} with the cluster virial mass, M_{500}, and cluster luminosity, L_X, for the entire sample, the SCC clusters showing a tighter trend in both the cases.

INTRODUCTION

The imprints of AGN activity on the physical properties of both, their host-galaxies and also host-halos are discernable in two, most likely connected, observational facts: 1) presence of an upper-mass end truncation of the galaxy distribution [e.g. 1] and 2) lack of copious amounts of cool gas in the central atmospheres of the so-called cool-core clusters [e.g. 2].

Numerous results have confirmed that radio-loud AGN dwell preferentially in brightest cluster galaxies, as opposed to other galaxies of the same stellar mass [e.g. 3]. It has also been found that the cool-core (CC) clusters are particularly conducive for radio-loud cD galaxies, even though the fraction of radio-loud cD galaxies in CC clusters varies from study to study ranging from 70% to 95% [4, 5, 6]. This is due to the varying selection criteria used for constructing cluster samples, different definitions for CC and non-CC (NCC) clusters, and the use of not so up-to-date X-ray and radio observations (see Mittal et al. 2008 for a few distinct examples of discrepant cases). This calls for a comprehensive study of a homogeneously selected and analysed cluster sample.

THE SAMPLE, X-RAY AND RADIO DATA

In [7] we carried out a detailed joint analysis of the largest complete local sample of galaxy clusters that has high-resolution X-ray data acquired from *Chandra*, *HIFLUGCS* [8]. This sample has a flux-limit of f_X $[(0.1-2.4)$ keV$] \geq 2\times10^{-11}$ erg s^{-1} cm^{-2} and a mean redshift ~ 0.05. The radio data are compiled from various sources spanning a wide range of frequencies. Our goal is to scrutinize the ways in which

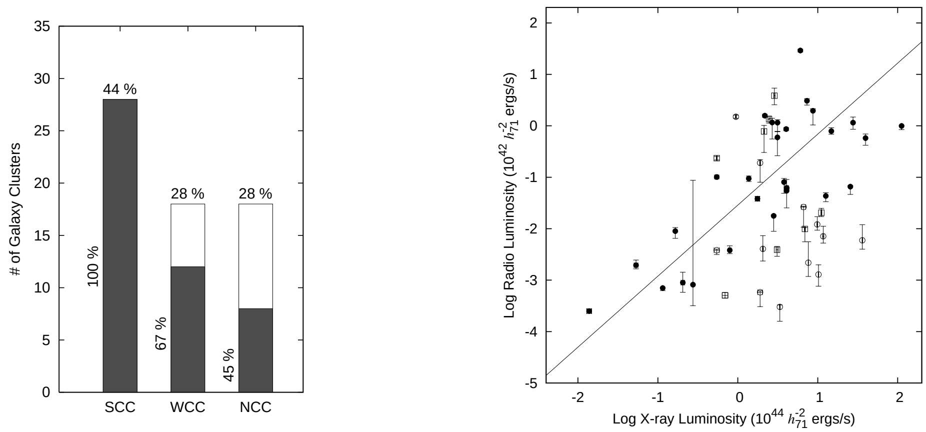

FIGURE 1. *Left*: The fraction of strong cool-core (SCC) clusters, weak cool-core (WCC) clusters and non-cool-core (NCC) clusters in the *HIFLUGCS* sample. Also shown are the fraction of clusters containing central radio sources for each category (shaded). *Right*: Total radio luminosity vs. *ROSAT* bolometric X-ray luminosity for SCC (filled circles), WCC (open circles) and NCC (open squares) clusters.

AGN heating is connected to the cooling of the ICM based solely on the total radio output, $L_{\rm R}$ (10 MHz-15 GHz), of the AGN [9].

We compiled and in many cases reanalyzed radio observations of all 64 clusters from either literature or archives [*VLA*, NVSS, VLSS and MOST]. We use of a total of $\sim$ 140 independent radio flux-density measurements, with data at more than two frequencies for more than 54% of the sources extending below 500 MHz, enabling the detection of spectral curvatures where present, and the determination of accurate estimates of $L_{\rm R}$ (we have recently acquired proprietary data for all but two of the remaining 35% clusters with no reliable data below 500 MHz with *VLA* at 325 GHz and with *GMRT* at dual-frequency band 610 MHz/235 MHz).

RESULTS I: CC AND NCC CLUSTERS WITH A CENTRAL RADIO SOURCE

A well-known problem related to cooling-flows has been that of choosing an apt diagnostic for determining a cool-core cluster. Based on the K-Mean Method (KMM) algorithm [10] as a test for bimodality (or tri-modality) in the X-ray derived parameters, [7] find the central cooling time, $t_{\rm cool}$, as the best measure for cooling to divide the CC and NCC clusters. Hence based on $t_{\rm cool}$, we classify clusters with $t_{\rm cool} < 1$ Gyr as strong cool-core (SCC) clusters, with 1 Gyr $< t_{\rm cool} <$ 7.7 Gyr as weak cool-core (WCC) clusters and with $t_{\rm cool} >$ 7.7 Gyr as non-cool-core (NCC) clusters. We find 48 out of 64 clusters (75%) contain cluster center radio sources (CCRS) cospatial with or within 50 h_{71}^{-1} kpc of the X-ray peak emission. Further, we find that the probability of finding a CCRS increases from 45% to 67% to 100% for NCC, WCC and SCC clusters, respectively (Fig. 1, left panel).

RESULTS II: COOLING AND AGN ACTIVITY

The right panel of Fig. 1 shows a strong positive correlation between $L_{\rm R}$ and cluster X-ray luminosity in SCC clusters, and also the classical mass deposition rate, $\dot{M}_{\rm classical}$, in SCC and partly also in WCC clusters (Fig. 2, left panel). The latter can be quantified as $L_{\rm R} \propto \dot{M}_{\rm classical}^{1.68\pm0.55}$.

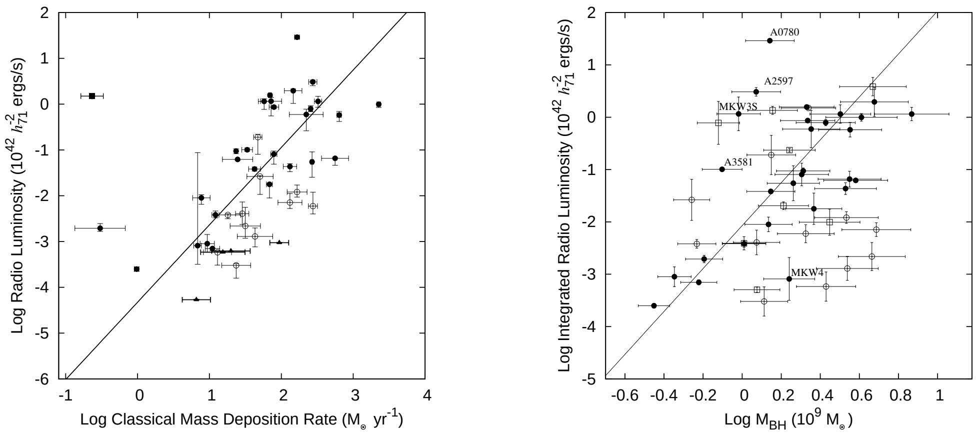

FIGURE 2. *Left*: Total radio luminosity vs. the classical mass deposition rate for SCC clusters (filled circles) and WCC clusters (open circles). The black triangles are four WCC clusters with $\dot{M}_{\rm classical} > 1$ and no central radio source. Hence, these are only upper limits. The filled square on top left is A2634, also a WCC cluster. The solid line is the best fit through CC clusters (SCC and WCC clusters combined) excluding A2634. *Right*: The mass of the SMBH versus the total radio luminosity of the BCG in SCC (filled circles), WCC (open circles) and NCC (open squares) clusters. A weak trend is visible (solid line) for the SCC clusters such that the $L_{\rm R}$ of the BCG increases with the SMBH mass. Labeled are the five outliers.

RESULTS III: BCGS, SMBHS AND LARGE-SCALE CLUSTER PROPERTIES

We also perform correlations of the luminosity of the brightest cluster galaxy, $L_{\rm BCG}$, close to the X-ray peak in all 64 clusters with $L_{\rm R}$ and cluster parameters, such as the virial mass, M_{500}, and the bolometric X-ray luminosity, $L_{\rm X}$. To this end, we use the 2MASS *K*-band magnitudes and invoke the near-infrared

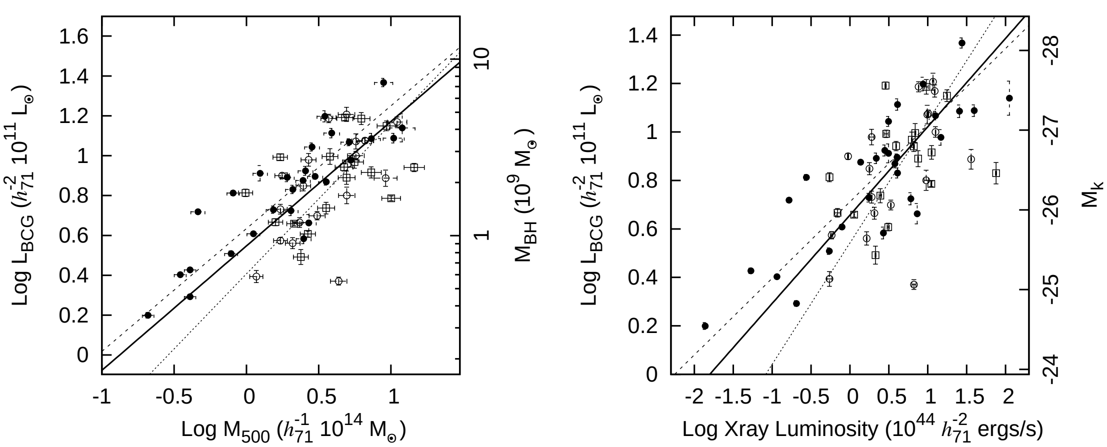

FIGURE 3. The 2MASS *K*-band total magnitudes of the 64 BCGs in the *HIFLUGCS* sample versus M_{500} in the left panel and *ROSAT* bolometric cluster X-ray luminosity in the right panel. Symbols are the same as in the left panel of Fig. 2. The solid, the dashed and the dotted lines denote the best-fit powerlaws for all clusters, only SCC clusters, and only non-SCC (WCCs+NCCs) respectively.

bulge luminosity-black hole mass relation to convert L_{BCG} to supermassive black hole mass, M_{BH}. We find a weak correlation between M_{BH} and L_{R} for SCC clusters, $L_{\mathrm{R}} \sim M_{\mathrm{BH}}^{4.07\pm0.422}$, although with a few outliers (Fig. 2, right panel). We find an excellent correlation of L_{BCG} with M_{500} and L_{X} for the entire sample, the trends being tighter for SCC clusters in both the cases (Fig. 3).

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