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Hot Gaseous Halos in Early Type Galaxies

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Abstract: The hot gas in early type galaxies (ETGs) plays a crucial role in their formation and evolution. As the hot gas is often extended to the outskirts beyond the optical size, the large scale structural features identified by Chandra (including cavities, cold fronts, filaments, and tails) point to key evolutionary mechanisms, e.g., AGN feedback, merging history, accretion/stripping, as well as star formation and quenching. We systematically analyze the archival Chandra data of ETGs to study the hot ISM. Using uniformly derived data products with spatially resolved spectral information, we revisit the X-ray scaling relations of ETGs and address their implications by comparing them with those of groups/clusters and simulations.

Keywords: galaxies: elliptical and lenticular; cD–X-rays: galaxies

1. Introduction

The hot gaseous halos in early type galaxies (ETGs) are closely connected to most important physical processes throughout a galaxy's evolution. These include the AGN feedback (e.g., preventing hot gas from cooling, producing X-ray cavities/bubbles related to radio jets), stellar feedback (stellar mass loss and SN ejecta being the main source of hot gas and chemical enrichment), interactions among galaxies (e.g., as revealed by cold fronts and sloshing) and with hotter ICM (e.g., ram pressure stripping), and the assembly of dark matter (being the main force that holds up the hot gas). With the sub-arcsecond resolution of the Chandra X-ray Observatory, we are now able to accurately measure global hot gas properties by effectively excluding LMXBs (low-mass X-ray binaries) and AGNs. Studying the physical properties of the hot halos allows us to address those important aspects of galaxy formation and evolution. In this conference proceedings paper, we review the previous studies and further discuss the implications by comparing the results of groups and clusters as well as the simulations.

2. X-ray Scaling Relations

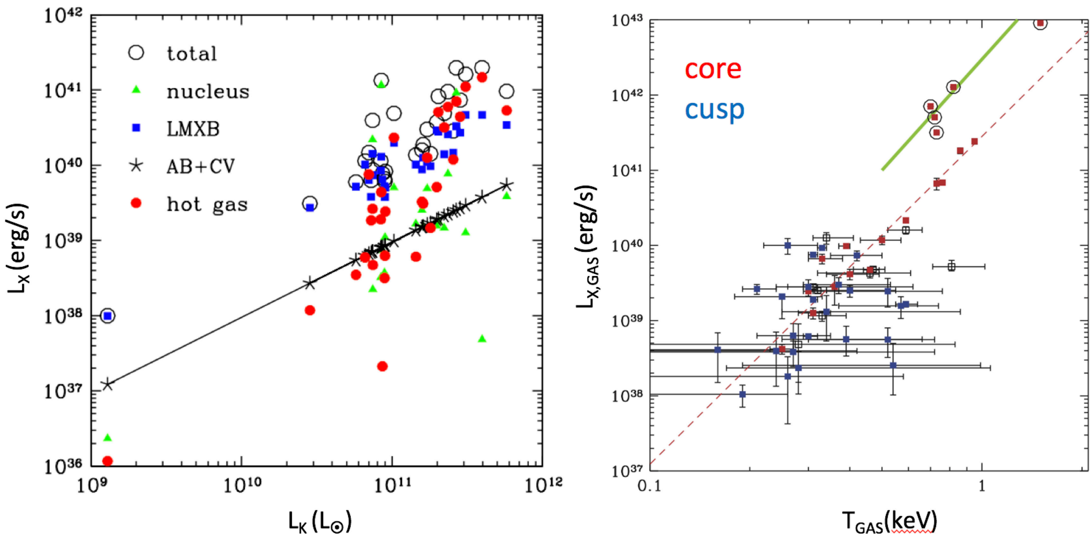
X-ray scaling relations have been widely used to investigate the origin and evolution of the hot ISM of ETGs [1–4]. Recent numerical simulation studies [5–8] have further attempted to reproduce the observed scaling relations, in order to constrain the physical mechanisms that shape the hot ISM.

2.1. $L_{X,GAS}$–L_K Relation

Chandra observations have given us the ability to separate the different X-ray emission components (e.g., nuclear, LMXB, AB + CV, hot gas) of ETGs to extract accurate measurements of $L_{X,GAS}$ [1]. This work has shown that the well-known factor of 100 spread in the previous ETG scaling relation, $L_{X,TOTAL}$–L_{OPT}, increases to a factor of 1000 when $L_{X,GAS}$ is used instead of $L_{X,TOTAL}$.

We plot the X-ray luminosities against the *K*-band luminosity in Figure 1 where different components are marked by different symbols. The contribution from ABs (active binaries) and CVs (cataclysmic variables), $L_{X,(AB+CB)}$, is marked by a linear diagonal line. The contribution from

LMXBs (blue squares), $L_{X,LMXB}$, is proportional to L_K, but with a non-negligible scatter. The LMXB integrated luminosity is about 10 times larger than that of ABs + CVs. The nuclear emission (green triangles) spans more than 2 orders of magnitude and does not seem to scale with L_K (see also [9]). The X-ray luminosity of the hot gas, $L_{X,GAS}$, after excluding all other components, ranges from a few $\times$ 10^{37} erg s^{-1} to a few $\times$ 10^{41} erg s^{-1}. We note that $L_{X,GAS}$ is often lower than $L_{X,LMXB}$, except for those gas rich ETGs with $L_{X,GAS} > 10^{40}$ erg s^{-1}. The $L_{X,GAS}$–L_K relation is still correlated, but with a large scatter, e.g., the ratio of $L_{X,GAS}/L_K$ spanning 3 orders of magnitude for a given L_K.



(**a**) (**b**)

Figure 1. (**a**) X-ray luminosities of individual components are plotted against the *K*-band luminosity. The total X-ray luminosity is denoted by open black circles, nuclei by filled green triangles, LMXBs by filled blue squares, and hot gas by filled red circles. Reproduced from Reference [1]; (**b**) X-ray luminosity and temperature of hot gas plotted separately for core and cusp galaxies. Those with big green circles are cDs. Reproduced from Reference [3].

2.2. *$L_{X,GAS}$–T_{GAS} Relation*

With Chandra, we have also been able to accurately measure the temperature of the hot gas by effectively removing point sources to derive the $L_{X,GAS}$–T_{GAS} scaling relation for ETGs. This relation is tighter than the $L_{X,GAS}$–L_K relation and may indicate virialization of the hot gas in the dark matter halos. The best fit relation is $L_{X,GAS} \sim {T_{GAS}}^{4.5}$ [1,3,4] when the cD galaxies are excluded. The relation is particularly tight for the normal (non-cD) core galaxies with a scatter of only 0.2 dex rms. This tight relation holds for a range of kT_{GAS} = 0.3–1 keV and $L_{X,GAS}$ = a few $\times$ 10^{38}—a few $\times$ 10^{41} erg s^{-1}. In contrast, no correlation exists for coreless (or cusp) galaxies (and spiral galaxies). This may be understood due to the presence of several factors in coreless galaxies (as in spiral galaxies) that may affect the retention and temperature of the hot gas. They include global rotation, flattened galaxy figures possibly with embedded disks, and recent star formation. See Figure 1a for a comparison of core and cusp galaxies.

In Figure 2, we show a schematic diagram comparing the $L_{X,GAS}$–T_{GAS} relations in the ETG samples with those reported for groups [10] and clusters of galaxies [11]. To the first approximation, the bigger the system, the hotter and more luminous the gas. The details are more complex, however. Starting from the bottom left corner, the coreless ETGs and spiral galaxies show no clear correlation. On the other hand, pure ellipticals (Es) show a tight correlation with a slope of 4.5. Furthermore, this tight relation is well-reproduced among σ-supported, hot gas rich elliptical galaxies by high-resolution simulations [5]. The groups follow a similar trend as the core Es, but are shifted toward higher $L_{X,GAS}$ values for a given T_{GAS}. The larger dark matter halo may be responsible for the retention of larger hot gaseous halos. (larger L_X). The clusters at the top right corner have a strong, but flatter relation ($L_{X,GAS} \sim T_{GAS}^3$). As the exact difference between groups and clusters is somewhat subtle, the distinction may be ambiguous among the big groups and small clusters (e.g., see [12]). The relation expected by the self-similar case (where gravity dominates) has a slope of 2 (dashed lines in Figure 2). The steep slope (3) in clusters indicates that baryonic physics is already important, even in the largest scale. In galaxies, the slope is even steeper (4.5), further indicating the increased importance of non-gravitational effects (including SF, AGN, and their feedback).

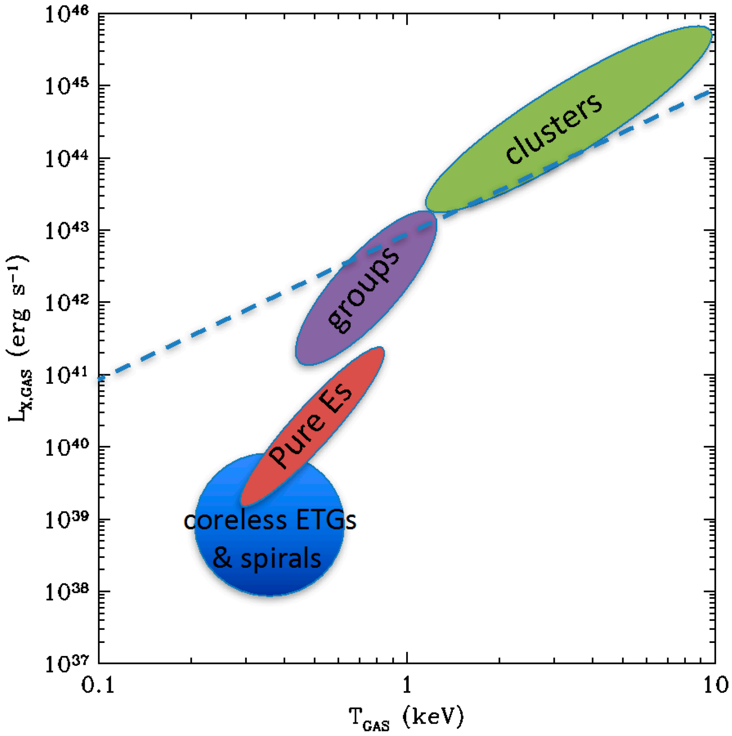


Figure 2. Comparison of the $L_{X,GAS}$–T_{GAS} relations in various samples. From the bottom left, the coreless ETGs and spirals have no correlation, while the normal (non-cD) core E galaxies have a very tight correlation ($L_{X,GAS} \sim T_{GAS}^{4.5}$). The groups have a similar trend as the core Es, but they are shifted toward higher $L_{X,GAS}$. The clusters at the top right corner have a flatter relation ($L_{X,GAS} \sim T_{GAS}^3$) compared to other sub-samples. For a reference, the self-similar expectation ($L_X \sim T^2$) is shown in dashed lines. Reproduced from Reference [3].

2.3. $L_{X,GAS}$–M_{TOTAL} Relation

The optical luminosity (L_K) is a good proxy for the integrated stellar mass of the galaxy, $M\star$; however, it does not measure the amount of dark matter (DM) mass, which may be prevalent, especially at large radii. The total mass (stellar + DM), out to radii comparable to the total extent of the hot halos of gas-rich ETGs, is the physical quantity we must know in order to explore the importance of gravitational confinement for the hot gas retention [2,13]. A number of dynamical mass measurements at large radii (within 5 R_e) have recently become available from the analysis of the kinematics of hundreds of globular clusters (GC) and planetary nebulae (PN) in individual galaxies [14,15]. With these improved X-ray and mass measurements, we have investigated the $L_{X,GAS}$–M_{TOTAL} relation [2,13] and found a tight correlation between these physically motivated quantities (even if the total mass is harder to measure than e.g., L_B or L_K). In a simple power-law form, the best fit relation is ($L_{X,GAS}/10^{40}$ erg s^{-1}) = ($M_{TOTAL}/3.2 \times 10^{11}$ $M_\odot$)^3 with an rms deviation of a factor of 3 in $L_{X,GAS} = 10^{38}$–10^{43} erg s^{-1} or M_{TOTAL} = a few $\times$ 10^{10}—a few $\times$ 10^{12} $M_\odot$. More strikingly, this relation becomes even tighter with an rms deviation of a factor of 1.3 among the gas-rich galaxies (with $L_{X,GAS} > 10^{40}$ erg s^{-1}). Our results [2,13] indicate that the total mass of an ETG is the primary factor in regulating the amount of hot gas. Since the gas temperature reflects the energy input and the depth of the potential well, the $L_{X,GAS}$–T_{GAS} relation provides a complementary scaling relation to $L_{X,GAS}$–M_{TOTAL}. Interestingly, the functional form of this relation (power-law with a slope of ~3) is consistent to what would be expected from the steep $L_{X,GAS}$–T_{GAS} relation found in the above, given that $M_{TOTAL} \sim T_{GAS}^{3/2}$ (virial theorem).

3. Discussion

3.1. Comparison with Clusters

The X-ray scaling relations are well established among clusters of galaxies where the larger amount of hotter (a few–10 keV) gas is retained inside the deeper cluster potential well. In Figure 3, we show three relations (L_X–T_X, L_X–M_{500}, M_{500}–T_X) reproduced from Reference [16]. All three relations are tightly correlated among clusters of galaxies. In Figure 3, we schematically overlay those of pure Es (NGC 3379 being the smallest and NGC 4649 being the largest among the E sample). The comparisons reveal that (1) L_X of the E sample is considerably lower than that extrapolated from the cluster sample and (2) the relations (L_X against T_X or M) of the E sample are significantly steeper, while the M–T_X relation follows each other. These distinctions imply that Es lost a large portion of hot gas [17], likely by AGN/stellar feedback, while clusters have retained most of their hot gas in a closed box. Both feedback mechanisms play a significant role in increasing the importance of non-gravitational effects and making the slope deviate more from self-similar behaviors.

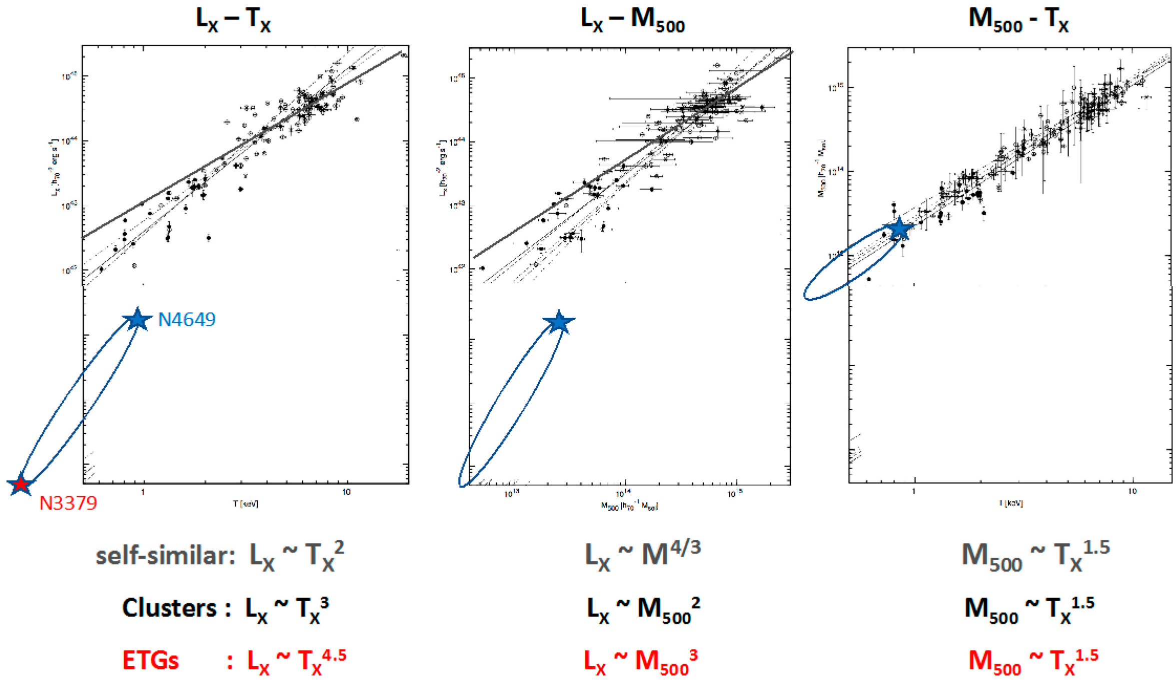


Figure 3. Comparisons of X-ray scaling relations of ETGs and clusters. From the left, $L_{X,GAS}$–T_{GAS}, $L_{X,GAS}$–M_{500}, and M_{X500}–T_{GAS} relations are shown. The black data points and black thin lines for clusters are reproduced from Reference [16], and the red regions indicate the core ETGs. The smallest (NGC 3379) and largest (NGC 4649) among our ETG samples are marked. The self-similar predictions ($L \sim T^2$ and $L \sim M^{4/3}$) are also marked by green thick lines.

3.2. Comparison with Simulations

Recent numerical simulations have been significantly improved. They can reproduce the observational results and compare the X-ray properties in detail [5–8]. References [5,6] applied 2D high-resolution hydro simulations and considered stellar feedback, dynamical (rotation), and structural (flattening) parameters as well as AGN feedback, and References [7,8] applied 3D cosmological simulations. While the differences among different simulations and different parameters/recipes are to yet be understood, in general they can reproduce the observed relations among $L_{X,GAS}$, T_{GAS}, M_{TOTAL} (or M within 5 Re). In particular, these studies suggested that the stellar and AGN feedback are important in the early epoch to globally reduce the amount of hot gas (or $L_{X,GAS}$) and the total mass to retain the hot gas afterward. Quantitative comparisons with observables and predictions in a specific sample of galaxies are to be performed in the future.

Conflicts of Interest: The authors declare no conflict of interest.

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