Stripping of the Hot Gas Halos in Member Galaxies of Abell 1795

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Abstract

The nearby cluster Abell 1795 is used as a testbed to examine whether hot gas in cluster galaxies is stripped by the ram pressure of the intracluster medium (ICM). The expected X-ray emission in and around Abell 1795 galaxies is likely dominated by the ICM, low-mass X-ray binaries, active galactic nuclei, and hot gas halos. In order to constrain these components, we use archival Chandra X-ray Observatory and Sloan Digital Sky Survey observations of Abell 1795 and identify 58 massive (M_⋆ > 10^{10} M_☉) spectroscopic cluster members within 5′ of the Chandra optical axis. X-ray images at 0.5–1.5 and 4–8 keV were created for each cluster member and then stacked into two clustercentric radius bins: inner (0.25 < R_{clust}/R_{500} < 1) and outer (1 < R_{clust}/R_{500} < 2.5). Surface brightness profiles of inner and outer cluster members are fit using Markov chain Monte Carlo sampling in order to generate model parameters and measure the 0.5–1.5 keV luminosities of each model component. Leveraging effective total Chandra exposure times of 3.4 and 1.7 Ms for inner and outer cluster members, respectively, we report the detection of hot gas halos, in a statistical sense, around outer cluster members. Outer members have 0.5–1.5 keV hot halo luminosities (L_X = (8.1^{+3.5}_{-3.5}) × 10^{39} erg s^{-1}) that are six times larger than the upper limit for inner cluster members (L_X < 1.3 × 10^{39} erg s^{-1}). This result suggests that the ICM is removing hot gas from the halos of Abell 1795 members as they fall into the cluster.

Key words: galaxies: clusters: general – galaxies: evolution – X-rays: galaxies

1. Introduction

The correlation between a galaxy’s star formation activity and its environment and look-back time has been known for quite some time. Relative to the low-density field environment, the star formation activity of galaxies in dense galaxy clusters is much lower (Balogh et al. 1997). Indeed, local clusters are predominantly populated by galaxies that are no longer forming stars (they are said to have been quenched or to be quiescent; Chung et al. 2011). Furthermore, observations of distant clusters reveal star formation activity that is higher than what is found locally (Tran et al. 2010), and in some cases as high as in the field (Brodwin et al. 2013; Alberts et al. 2014). Clearly, environment has played a significant role in quenching (turning off) the star formation of galaxies.

Galaxies become quiescent through the depletion of the cold gas necessary for the formation of new stars. Several mechanisms, which act over very different timescales, have been proposed to explain the observed quenching of star formation in cluster galaxies over time. Active galactic nuclei (AGN) feedback is a short-timescale quenching process (~100 Myr; Di Matteo et al. 2005) that can heat and expel cold interstellar gas (Hopkins et al. 2006). Ram-pressure stripping (RPS; Gunn & Gott 1972) will also quickly (<1 Gyr; Quilis et al. 2000) remove a galaxy’s neutral gas due to the pressure exerted as it moves through the diffuse intracluster medium (ICM). This differs from the much slower process of strangulation (>1 Gyr; Larson et al. 1980), by which the loosely bound hot halo of a galaxy can be stripped by the same ram pressure during infall into the cluster. The in situ cold gas, however, is not removed, and the galaxy can continue to form new stars until this supply is depleted, which can take several Gyr.

While the above quenching mechanisms all act on some level in clusters, recent observational studies provide indirect support for strangulation being the dominant process. These lines of evidence include the elevated stellar metallicities in cluster galaxies (Peng et al. 2015), consistent with long quenching timescales, and stellar populations that indicate long periods of persistent low-level (compared to the field) star formation (Paccagnella et al. 2016). However, a more direct approach can be taken: measuring the gas content of galaxies as a function of environment. From an X-ray perspective, the observational signature of strangulation would be a transition around the virial radius of galaxy clusters from gas-rich hot halos at large clustercentric radius to gas-poor hot halos in the inner cluster.

Ideally, one would measure the hot halo luminosity for all cluster galaxies as a function of clustercentric radius. However, the electron density of individual halos is n_e ~ 10^{-4} cm^{-3} (Bogdán et al. 2013), which is comparable to that of the ICM in the cluster outskirts, making their detection challenging. Worse, in cluster cores, the ICM density can be as high as ~10^{-2} cm^{-3} (Zandanel et al. 2014), which limits direct detection to only the most luminous cluster galaxy halos (e.g., Sun et al. 2007). While direct detection likely is not feasible for the vast majority of a cluster’s galaxies, hot halos can be detected in a statistical sense by stacking X-ray images of cluster members to derive the average X-ray emission of a population of galaxies. This stacking method has been used to detect diffuse hot halos around isolated field galaxies (e.g., Bogdán & Goulding 2015). In addition to the ICM, there are a number of other sources that contribute to the overall X-ray emission around cluster galaxies. These include low-mass X-ray binaries (LMXBs), high-mass X-ray binaries (HMXBs), AGNs, and hot halos (if they are still around cluster galaxies).

In this work, we construct models that account for the dominant sources of X-ray emission. This allows us to measure, in an average sense, the X-ray luminosity of each component and enables us to infer whether cluster members...
have retained their hot gas halos. To implement our models, we stack archival Chandra X-ray Observatory images of the nearby (z = 0.0622; Vikhlinin et al. 2006) cluster Abell 1795 (A1795) and generate surface brightness profiles (SBPs) in two clustercentric radius bins. A Markov chain Monte Carlo (MCMC) sampling code is used to fit the SBPs and derive the contribution from each model component.

Our data sets and sample selection are presented in Section 2, while we describe our model and the results of our SBP fitting in Section 3. We discuss our results in Section 4 and summarize our findings in Section 5. Throughout, we adopt a WMAP7 cosmology (Komatsu et al. 2011) with (ΩΛ, ΩM, h) = (0.728, 0.272, 0.704). In this cosmology, A1795 has a luminosity distance of 277.7 Mpc.

2. Data and Sample Selection

2.1. SDSS

The optical portion of our data comes from the Sloan Digital Sky Survey (SDSS) Data Release 12 (Alam et al. 2015). The SDSS provides positions and spectroscopic redshifts for 864 galaxies located within 50′ (~3.6 Mpc) of A1795, whose position is taken from Shan et al. (2015). Our cluster membership uses the redshift selection criterion from Shan et al. (2015), which gives a redshift membership range of 0.0552 < zgal < 0.0692 for A1795 based on its velocity dispersion. This cut, which results in 190 galaxies, is very conservative and will likely exclude some bona fide A1795 members. However, as background and foreground galaxies will have hot halos, including them could bias our stacked X-ray images.

Using the R500 for A1795 from Vikhlinin et al. (2006), members are separated into two clustercentric radius (Rclust) bins: 0.25 < Rclust/R500 < 1 and 1 < Rclust/R500 < 2.5. Galaxies within the inner 25% of R500 are excised to reduce contamination from the ICM.

We match our member list to the catalog of Chang et al. (2015), who measured star formation rates (SFRs) and stellar masses using SDSS and WISE photometry for the spectroscopic SDSS sample compiled by Blanton et al. (2005). This results in 135 members with SFRs and stellar masses that are located within 0.25 < Rclust/R500 < 2.5.

Even though low-mass galaxies are the most numerous in galaxy clusters, they will have their hot halos stripped more quickly than higher-mass galaxies (Vijayaraghavan & Ricker 2015). As our goal is to detect the presence of hot halos around A1795 members, we impose a minimum stellar mass cut of 10^10 M⊙ on our sample. Figure 1 shows the distribution of stellar masses for our final sample. The remaining sample cuts will be described in Section 2.2.

The SDSS i-band images that cover the A1795 field of view are downloaded and then mosaicked using MONTAGE (version 5.0; Jacob et al. 2010a, 2010b). SEXtractor (Bertin & Arnouts 1996) is used to identify stars in the mosaicked image, and their positions are masked with zero values. Individual 103″ × 103″ cutouts are made for each cluster member from the i-band SDSS mosaic. For each clustercentric radius bin, SDSS images are then stacked, and SBPs are calculated (see Section 2.3). The i-band data will provide us with a proxy for the LMXB populations within A1795 members (see Section 3.3).

We stack images by taking the median value at each pixel instead of the mean. While the overall shapes of the SBPs are similar (especially toward the center of the stacks) between the two types of images, those created by taking the median value at each pixel have smoother shapes, as they are not as impacted by outliers (i.e., light from nontarget galaxies). Figure 2 shows a comparison of a single i-band image (top left) with median-stacked images of multiple galaxies. While the image of the single galaxy is clearly nonisotropic, individual galaxy features are smoothed over as more galaxies are included in the stack. With 25 galaxies, the stack is highly smooth and circular.

We inspect the i-band images of the final A1795 members and find that 10 of the 58 galaxies have obvious late-type features, with five in each clustercentric radius bin. This results in early-type galaxy fractions of 0.84±0.07 and 0.81±0.08 for the inner and outer cluster, respectively.

2.2. Chandra

We have acquired 170 Chandra observations covering A1795 out to 50′ (~3.6 Mpc) from the Chandra Data Archive.5 We match the observation positions against those of our galaxy sample in order to select the 58 members that fall within 5′ of the Chandra optical axis in at least one observation (and also meet the mass and clustercentric radius cuts described in the previous section). As the Chandra point-spread function (PSF) is strongly dependent upon the position within the telescope’s field, degrading as a function of off-axis angle, this selection helps mitigate PSF broadening.

Our sample was observed, on average, four times per galaxy, for a total sample exposure time of 5.1 Ms, with 3.4 Ms for the

\[ \text{http://montage.ipac.caltech.edu/} \]

\[ \text{http://cda.harvard.edu/chaser/} \]

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\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure1.pdf}
\caption{Distribution of stellar masses for our final sample. The majority of galaxies in both clustercentric radius bins are concentrated in a fairly narrow range in stellar mass between M_⋆ = 10^{10} (our lower-mass cut) and M_⋆ ∼ 5 × 10^{10} M_\odot.}
\end{figure} 
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values, which ensures that the exposure-corrected images have exposure-corrected galaxy was observed. All individual events stacked and averaged for each clustercentric radius bin. The averaged for each multiple-exposure galaxy, then all cutouts are excluded more than 5″ in each exposure-corrected image. We only exclude sources that members. The exposure-corrected cutouts are exposure-corrected images have units of exposure-corrected images are shown in Figure 3. We extract SBPs for each of these stacks, as described in the following section. Because the exposure-corrected images have units of flux, the SBPs are in units of flux per area.

In order to identify individually detectable objects, we first estimate our sensitivity in the soft X-ray images. For each cutout, we iteratively add a single count to a random position in the image within a 5′′ × 5′′ region (−2″5 × 2″5). To ensure that we are not adding flux to the target, counts are only added outside of the central 50′′ × 50′′ pixels (−25″ × 25″) of the cutout. After each count has been added, we run wavdetect. This process is repeated until a new source has been detected, at which point we exposure-correct the modified cutout. The background flux of the cutout is measured using a large area that does not intersect with the target, artificial source, or any sources originally detected in the image. The region defined by wavdetect is used to sum the flux of the added source, which is converted into a luminosity with $L_X = 4\pi d_L^2 f_X$, where $d_L$ is the luminosity distance of A1795 and $f_X$ is the X-ray flux.

Background-subtracted luminosities are calculated for sources detected in each cutout, as long as the source is located at the center of the image. A target is flagged as detected if its background-subtracted luminosity is at least as large as the sensitivity limit found above. Four such objects are found, all lying beyond $R_{500}$. Formally, our detection fractions are $0.00^{+0.06}_{-0.00}$ and $0.15^{+0.11}_{-0.07}$ for the inner and outer cluster, respectively.

We investigate fitting the SBPs of the individually detected galaxies. For three of the galaxies, there are not enough data to generate SBPs with fine enough binning to accurately model the inner portions of the profile. The remaining galaxy has substantially more data, but upon fitting the galaxy’s SBP, the residuals are so large that it prevents any meaningful analysis. However, we find no evidence in any of the four profiles of an extended component beyond what could be expected from a combination of an AGN, LMXBs, and the ICM. While these galaxies likely contribute a significant portion of the data in the stacked profile, we cannot analyze them individually. Hence, we do not remove them from our stacked outer cluster SBP; this is akin to measuring SFRs with stacked infrared observations.

Figure 2. Comparison of a single i-band image and median-stacked images with five, 10, and 25 different galaxies. Each image is 260 pixels (~103″) per side. Median stacking of the optical images results in a smooth and relatively isotropic SBP.

Figure 3. Stacked X-ray images for the inner (left) and outer (right) cluster for both soft (top) and hard (bottom) X-rays. Each image is 101 pixels (~50″) per side. When compared to the outer cluster, the inner cluster’s relatively high background is evident at 0.5–1.5 keV. Any potential gradient in the background due to telescope orientation has been removed through the stacking procedure.

32 galaxies at low clustercentric radius and 1.7 Ms for the 26 galaxies in the outer cluster.

All observations are reprocessed using CIAO version 4.9 (Fruscione et al. 2006) and version 4.7.6 of the Chandra Calibration Database. For each observation, exposure maps are created with CIAO’s fluximage script, and PSF maps are generated with mkpsfmap. We then run wavdetect to detect sources in each observation. For each galaxy, we make $50'' \times 50''$ cutouts over the 0.5–1.5 keV (soft X-ray) and 4–8 keV (hard X-ray) ranges from the exposure maps and the reprocessed events files. For the galaxies that were observed more than once, cutouts are made from each exposure map and events file in which the galaxy was observed. All individual events file cutouts are then exposure-corrected with fluximage using the script’s default values, which ensures that the exposure-corrected images have units of flux (photons s$^{-1}$ cm$^{-2}$). Using dmcopy with the exclude filter, the source positions detected above are masked in each exposure-corrected image. We only exclude sources that lie more than 5′′ away from the center of the cutout (i.e., the galaxy’s location) to ensure that we do not mask our final sample members. The exposure-corrected cutouts are first stacked and averaged for each multiple-exposure galaxy, then all cutouts are stacked and averaged for each clustercentric radius bin. The final stacked images are shown in Figure 3. We extract SBPs for each of these stacks, as described in the following section. Because the exposure-corrected images have units of flux, the SBPs are in units of flux per area.

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2.3. Measuring SBPs

We define 52 (15) concentric annuli for the stacked Chandra (SDSS) images, centered on the middle of the pixel that corresponds to the target’s location. In general, the SBPs are then defined by summing the flux in all pixels in each annulus, then dividing by the area of the annulus. Starting with the innermost annulus and working outward, pixels are considered to be in an annulus if the center of the pixel is contained within the annulus’s radius. The entire flux from that pixel is then considered to be in that annulus. The sum of the flux from all pixels in each annulus is divided by the area, which is the total number of pixels. This initial surface brightness is then divided by the square of the pixel scale to give a surface brightness in terms of square arcseconds. For fitting and plotting purposes, the corresponding radius point for each surface brightness value is redefined as the midpoint between the current and previous annulus radius.

3. Modeling the X-Ray Emission from Member Galaxies in A1795

In this section, we will describe some of the components that can be expected to contribute to X-ray emission in and around galaxies in A1795, with the initial simplifying assumption that A1795 members no longer possess a hot halo. Hence, we expect X-ray emission only due to AGNs (Section 3.1), the ICM (Section 3.2), and/or X-ray binaries (XRBs; Section 3.3). To test our assumption, we will build models that incorporate these components and assess how well they fit the X-ray SBPs of stacked A1795 members. We shall refer to the position within the galaxies’ stacked images as the galactocentric radius, $R_{\text{gal}}$.

3.1. AGNs

In our SBPs, the emission due to an AGN takes the shape of the Chandra PSF. To accurately model the PSF at various positions on the detector, we use the SAOTRACE (v2.0.4; Jerius et al. 1995)\(^5\) ray-tracing code to simulate light rays through the telescope optics and MARX (v5.3.2; Davis et al. 2012)\(^6\) to create PSF images. The resulting PSF images—one for each galaxy for each observation in which it was observed—are multiplied by the total flux in a 1” radius aperture around the target position in the respective reprocessed observations. For each galaxy, all of its PSF images are stacked and averaged. As with the X-ray images, these resulting images are also stacked and averaged after being separated into two clusterentric radius bins. As a function of galactocentric radius, $I_{\text{PSF}}(R_{\text{gal}})$, SBPs are then extracted for each of the PSF stacks, following the method described in Section 2.3.

In order to account for PSF differences between optical and X-ray data, we generate a convolution kernel, PSF, from each PSF SBP, which will be used to convolve some components in our models.

3.2. The ICM

A constant component is used in all of our X-ray fits to account for the cluster background. The background in individual X-ray cutouts may have a gradient that depends on the galaxy’s position in the cluster and the orientation of the telescope at the time of observation. However, our average stacked images of multiple galaxies over multiple observations effectively remove any such gradient, as can be seen by the relatively isotropic background in all four panels of Figure 3.

3.3. XRBs

To determine the expected relative significance of each type of XRB system in A1795 galaxies, we use relations from the literature to estimate their X-ray luminosities. In each case, we scale the relation from the energy range in the published work to our energy range of interest, 0.5–1.5 keV, using WebPIMMS.\(^7\) The HMXB spectrum is modeled as a power law with a photon index of 2.1 (Sazonov & Khabibullin 2017), while the LMXB spectrum is treated as a 7 keV thermal bremsstrahlung (Boroson et al. 2011).

For HMXBs, we use the relation between SFR and HMXB X-ray luminosity from Mineo et al. (2012); their Equation (39)), which, when scaled to our energy range, gives an expected HMXB luminosity of

$$L_{\text{HMXB}}^{0.5–1.5\text{ keV}} / (\text{erg s}^{-1}) = 1.06 \times 10^{39} \text{ SFR} / (M_\odot \text{ yr}^{-1}).$$

To find the expected X-ray luminosity due to LMXBs, we use the relation between stellar mass and LMXB X-ray luminosity from Zhang et al. (2012).\(^8\) Scaled to our desired energy range, this results in an expected LMXB luminosity of

$$L_{\text{LMXB}}^{0.5–1.5\text{ keV}} / (\text{erg s}^{-1}) = 2.48 \times 10^{39} M_\odot / (10^{11} M_\odot).$$

We calculate the ratio of the expected 0.5–1.5 keV luminosity due to HMXBs and LMXBs ($L_{\text{HMXB}}^{0.5–1.5\text{ keV}} / L_{\text{LMXB}}^{0.5–1.5\text{ keV}}$) for our final sample and plot their distribution in Figure 4. The mean ratio in each clusterentric radius bin is shown by the dashed vertical line. For outer cluster galaxies, the expected luminosity due to HMXBs is an order of magnitude lower than that due to LMXBs. In the inner cluster, HMXBs are expected to contribute less than 1% of the XRB flux. Because of their substantially lower expected 0.5–1.5 keV luminosity, we can safely exclude HMXBs from our analysis.

The companion in an LMXB system is typically an older, low-mass star. Since cluster galaxies are comprised mainly of old stellar populations, and LMXBs are not expected to be distributed differently than the underlying old stellar population, we will use the distribution of old stars in A1795 galaxies to model the shape of the LMXB contribution. The $i$-band SDSS images provide excellent proxies for the old stellar populations.

We perform a least-squares fit to each of the SDSS SBPs measured in Section 2.1, modeling the profiles with two Sérsic (Sérsic 1963) functions plus a constant. During fitting, the sum of the Sérsic functions and the constant is convolved with a Gaussian whose standard deviation is approximately the median value of the SDSS $i$-band PSF ($\sigma = 0.74$).\(^9\) The results of these fits are shown in Figure 5. The nonconvolved double Sérsic function, $S_i(R_{\text{gal}})$, is used to describe the shape of the LMXB component in our X-ray emission model. The LMXB ($i$-band) surface brightness component is

$$I_i(R_{\text{gal}}) = [S_i(R_{\text{gal}}) \ast \text{PSF}].$$

\(^5\) http://cxc.harvard.edu/cal/Hrma/SAOTrace.html
\(^6\) http://space.mit.edu/cxc/marx/
\(^7\) https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl
\(^8\) $L_{0.5–1.5\text{ keV}} / M_\odot = 9.6 \times 10^{39} \text{ erg s}^{-1} \text{ per } 10^{11} M_\odot$
\(^9\) http://www.sdss.org/dr12/imaging/other_info/
In this equation, the Sérsic function is convolved with the PSF kernel.

### 3.4. Modeling X-Ray Emission with an AGN, LMXB, and Background

Before describing our models, we first present the 0.5–1.5 keV SBPs (black points and error bars) in the upper panels of Figure 6. These SBPs are measured from the stacked images shown in Figure 3, using the procedure outlined in Section 2.3. While centralized emission can be seen in the stacked inner cluster SBP, it is not immediately obvious in the upper left panel of Figure 3. Although we do not present it, a smoothed image makes the emission apparent.

The magenta curves in Figure 6 show the ray-traced PSFs that we modeled in Section 3.1. Given that the shapes of the PSFs (and the AGN emission they imply) are fixed, and all that can be adjusted are their amplitudes, it is clear that an AGN alone cannot account for all the flux in and around A1795 members in either clustercentric radius bin.

The arbitrarily scaled PSF (AGN) reasonably fits (by eye) the first few SBP values at low $R_{\text{gal}}$ for both the inner and outer cluster galaxies. Qualitatively, the main deficit in an AGN-only model is that it cannot account for the background flux (the relatively flat SBP values at large $R_{\text{gal}}$). To remedy this, we define our first model,

$$I(R_{\text{gal}}) = C + A_{\text{AGN}} I_{\text{PSF}}(R_{\text{gal}}),$$

where $C$ is the (constant) ICM background, and $A_{\text{AGN}}$ is the multiplicative factor for $I_{\text{AGN}}(R_{\text{gal}})$, the surface brightness contribution due to an AGN. With this AGN+BG model defined, we use MCMC sampling to determine the contribution of each component, enabling us to generate model SBPs. We use the MCMC sampling code EMCEE (Foreman-Mackey et al. 2013),\(^8\) which uses sets of Markov-chain walkers to explore the parameter space, with each walker starting from some initial assigned value. To determine initial values of $A_{\text{AGN}}$ and $C$, we take the amplitude of our scaled PSF and the median of the 20 outermost SBP values, respectively. We use 400 walkers per parameter, each starting at a random value within 0.1% of the initial input. Using uniform priors on our parameters ($A_{\text{AGN}} \geq 0$ and $C \geq 0$), we run EMCEE for 1600 steps and cut the first 100 steps for burn-in. This results in $6 \times 10^5$ sets of parameters (i.e., $6 \times 10^5$ values for each parameter). This process is the same for both the inner and outer cluster.

We generate an SBP for each parameter set and find the 15th, 50th, and 85th percentiles of these profiles at each galactocentric radius. The sampled SBPs are plotted in red in the upper panels of Figure 6. The lower panels show the relative residuals between the AGN+BG model and 0.5–1.5 keV SBP ([data-model]/model). We use the Python package UNCERTAINTIES\(^9\) to derive errors on the relative residuals by propagating the uncertainties on the measured and model SBPs. For the model SBP, we treat the 15th and 85th percentiles as the uncertainty range. The relative residual is plotted with a solid line, and the uncertainty range is shaded.

\(^8\) http://dan.iel.fm/emcee/current/
\(^9\) https://pythonhosted.org/uncertainties/
Qualitatively, the AGN+BG model fits the background fairly well in both the inner and outer cluster, but the overall fit is poor. More specifically, the surface brightness is overestimated at low $R_{\text{gal}}$ and underestimated at moderate $R_{\text{gal}}$ (around $\sim 2''$ in the inner cluster and $2'' \lesssim R_{\text{gal}} \lesssim 7''$ in the outer cluster). This is due to the shape of the model interior to the background being driven only by the PSF. Using the median model SBPs, we calculate reduced $\chi^2$ values of 3.02 and 4.26 for the inner and outer cluster, respectively. These values suggest what was also determined qualitatively: an AGN+BG model is not sufficient to account for the X-ray flux of A1795 members.

We now consider a model that includes all the components previously described in this section: the cluster background, LMXBs, and AGNs. We reiterate our initial assumption that none of the X-ray emission is due to a hot gas halo from individual galaxies. The general form of this AGN+Stellar+BG model is

$$I(R_{\text{gal}}) = C + A_i I_i(R_{\text{gal}}) + A_{\text{AGN}} I_{\text{PSF}}(R_{\text{gal}}).$$

(5)

where $I_i(R_{\text{gal}})$ is the $i$-band SBP from Equation (3), $A_i$ is the multiplicative factor modulating the $i$-band Sérsic, and $A_{\text{AGN}}$ and $C$ are defined as in Equation (4).

Figure 6. Upper panels: SBPs of stacked 0.5–1.5 keV images of A1795 members (black points and error bars). Red curves are the median SBPs of the AGN+BG model, which comprises a background (constant) and an AGN (simulated Chandra PSF). The green curves show the SBPs of the AGN+Stellar+BG model, which includes an additional LMXB ($i$-band SDSS) component. The blue curve in the upper right panel is the median SBP of the AGN+Stellar+BG+Halo model, which further adds a hot halo component ($\beta$ function). The shaded regions show the 15th to 85th percentile range of the model SBPs. All model SBPs are generated through MCMC simulations. For both outer cluster runs that have an LMXB component (green and blue curves), the distribution of $i$-band–to–X-ray ratios from the inner cluster MCMC run with the AGN+Stellar+BG model (green curve) is used as a prior. The dashed magenta lines show the simulated PSF, scaled so that the innermost point equals the innermost point of the AGN+Stellar+BG model. This shows that an AGN-only model is not sufficient to account for the X-ray profile in either clustercentric radius bin. Lower panels: relative residuals ($\left[\frac{\text{data-model}}{\text{model}}\right]$) of the measured and model SBPs. Relative residuals are color coded to match their respective model, the uncertainty ranges are shaded, and the lines are slightly shifted to the left and right for clarity.
EMCEE. For this model, we use 500 walkers per parameter, assigning their starting values as before. We run EMCEE for 2500 steps, cutting the first 500 for burn-in, resulting in one million sets of parameters.

The upper left panel of Figure 6 presents the sampled inner cluster SBP for the AGN+Stellar+BG model in green. The relative residuals for this model are plotted with the same color in the bottom left panel. Qualitatively, the overall fit is good due to the extra flexibility provided by the LMXB term. The large residuals that were present in the AGN+BG model have been reduced slightly.

Quantitatively, the $\chi^2$ drops from 147.7 for the AGN+BG model to 138.2 for the AGN+Stellar+BG model. This drop of 9.5 in $\chi^2$ with only one less degree of freedom (through the addition of the LMXB’s $A_i$ term) results in a subtle improvement in the reduced $\chi^2$, which decreases from 3.02 to 2.88 for the inner cluster AGN+Stellar+BG model. The qualitatively better fit of the AGN+Stellar+BG model, coupled with its lower reduced $\chi^2$, validates the addition of the LMXB term. While a reduced $\chi^2$ of 2.88 may suggest that an additional component could be added to the model, it might also be a symptom of the scatter of the background. We will revisit the topic of potentially adding more terms to this model for the inner cluster, but we must first turn to the outer cluster.

To determine initial parameter values for the MCMC sampling at $R_{\text{dust}} > R_{500}$, we perform a least-squares fit between the AGN+Stellar+BG model and the SBP of the outer cluster. Since $A_i$ is effectively a scaling factor between the $i$-band and X-ray emission, it should be independent of position within the cluster, so during this fit, we fix $A_i$ at the value found during the least-squares fit of the inner cluster. This results in best-fit parameters for the background and AGN components, which we assign as the initial values for the EMCEE simulation. We use 500 walkers for each of the three parameters in the outer cluster EMCEE run, assigning them for the background and AGN components as we did for the inner cluster. For the amplitude of the LMXB component, we draw 500 random values from the inner cluster $A_i$ distribution. In addition to ensuring that the amplitudes of the AGN and constant components are nonnegative, we also use the inner cluster $A_i$ distribution as a prior and require $A_i$ to fall between the minimum and maximum of the inner cluster distribution. Following our procedure for the inner cluster, we run EMCEE for 2500 steps for the outer cluster, cutting the first 500 steps for burn-in. Using the resulting one million sets of parameters, we generate one million AGN+Stellar+BG model SBPs. The sampled model SBPs (relative residuals) are plotted in green in the upper (lower) right panel of Figure 6.

The AGN+Stellar+BG model fits the data well at low galactocentric radius, with relative residuals consistent with zero for $R_{\text{gal}} \lesssim 1''$. However, the residuals increase to order unity, as the model cannot accurately account for the X-ray flux between $\sim 2''$ and $\sim 10''$. With a reduced $\chi^2$ of 2.60, the AGN + Stellar+BG model better fits the measured SBP than just the AGN+BG. However, it clearly cannot account for all of the 0.5–1.5 keV flux.

Allowing $A_i$ to freely vary between clustercentric radius bins may produce a better fit in the outer cluster. However, this would imply that the scaling relation between the $i$ band and the X-ray is a function of clustercentric radius, and we can invoke no physical basis for such a claim. While the reduced $\chi^2$ of 2.60 may be in part due to the scatter of the data, the discrepancy between $\sim 2''$ and $\sim 10''$ suggests a shortcoming of the AGN+Stellar+BG model.

Quantitatively, it is clear that the AGN+Stellar+BG model does not accurately fit the SBP in the outer cluster. This result, along with a reduced $\chi^2$ of 2.60, suggests that augmenting this model with an additional component is warranted in order to more adequately account for all the X-ray emission from $R_{\text{dust}} > R_{500}$ galaxies.

To test whether the order in which we perform the fits (inner cluster followed by outer cluster) is the cause of the low-quality fit of the AGN+Stellar+BG model in the outer cluster, we repeat the analysis with this model but perform the fits and MCMC simulations on the outer cluster before the inner cluster. We do not present these results but note that the AGN + Stellar+BG model fits the SBP in the outer cluster slightly better than with the original analysis order. However, there is still an excess of flux near 10'', and the fit of the SBP in the inner cluster is much worse, more so than with the AGN+BG model. Hence, we conclude that the order of the fit is not the cause of the large flux excess in the AGN+Stellar+BG fit of the outer cluster.

### 3.5. Modeling the X-Ray Excess

In order to better account for the X-ray flux excess at $2'' \lesssim R_{\text{gal}} \lesssim 10''$ in the outer cluster, we now modify our AGN+Stellar+BG model by including a $\beta$ model (Cavaliere & Fusco-Femiano 1978), which has an SBP of

$$I(R_{\text{gal}}) = I_0 \left(1 + \left(\frac{R_{\text{gal}}}{R_c}\right)^{2\beta+2}\right)^{-\frac{3\beta+1}{2}}$$  

(Anderson & Bregman 2014), where $I_0$ is the central surface brightness (when $R = 0$) and $R_c$ is the core radius. The $\beta$ model is commonly used to model hot halos around galaxies (Anderson & Bregman 2014), and its inclusion is motivated in part by the results of Vijayaraghavan & Ricker (2015), who found, using synthetic X-ray observations, that hot halos should be detectable in stacked low-energy (0.1–1.2 keV) galaxy images out to $\sim 10''$ at $z = 0.05$. Given the location of the flux excess in our outer cluster SBPs, the $\beta$ model seems like the ideal choice to augment the AGN+Stellar+BG model.

As with the Sérsic component in the AGN+Stellar+BG model, the $\beta$ component is convolved with the PSF surface brightness kernel. In our new model, which we will call the AGN+Stellar+BG+Halo model, $I_0$, $R_c$, and $\beta$ are free parameters, with the constraints that $I_0$ must be nonnegative, $\beta$ can vary between 0.3 and 0.9, and the core radius must be in the range $0''08 < R_c < 8''5$.

Following the procedure outlined in Section 3.4, we find the best fit between the X-ray surface brightness in the outer cluster and the AGN+Stellar+BG+Halo model using the best-fit parameter values as inputs into EMCEE. As with the AGN + Stellar+BG model EMCEE run, we use the $A_i$ distribution of the inner cluster as a prior, also drawing from it to seed the initial walker values.

Given that we have three additional parameters for this model, we use 2500 walkers and run EMCEE for $1 \times 10^5$ steps. The amount of run time required for the walkers to fully explore the parameter space is much larger than with any of the previous models, and we discard all but the last 5000 steps of the run for burn-in. This results in 12.5 million sets of
parameters that are used to generate SBPs, which are plotted in
blue in the upper right panel of Figure 6, with the relative
residuals shown in the bottom right panel with the same color.
Qualitatively, the fit in the outer cluster with this new model
is substantially better than with either of the previous two
models. All of the X-ray excess at $2'' \lesssim R_{\text{gal}} \lesssim 10''$ has been
accounted for. With a reduced $\chi^2$ of 1.62, the fit is also
quantitatively superior and validates the addition of the $\beta$
component in the outer cluster.

Given these positive results, we repeat the analysis on the
inner cluster with the AGN+Stellar+BG+Halo model. While
we do not plot the modeled SBP, qualitatively, the fit is
consistent with the results of the AGN+Stellar+BG model.
Furthermore, with a $\chi^2$ of 139.1, the quality of the fit is no better
than with the AGN+Stellar+BG model, and with the addition of
the three $\beta$ parameters, the reduced $\chi^2$ increases to 3.09. These
results suggest that a hot halo component is unnecessary for
fitting the 0.5–1.5 keV SBPs of inner cluster A1795 members.

3.6. Hard X-Ray SBPs

In this section, we repeat our analysis for hard X-ray
(4–8 keV) SBPs of A1795 members to test whether our soft
X-ray model components are appropriately modeling their
intended physical counterparts. Specifically, we focus on the
hot halo in the outer cluster. Given the temperature of galaxy
hot halos ($\sim 10^7$ K; Forman et al. 1985), which corresponds to
$kT \sim 0.9$ keV, their expected X-ray emission should fall
primarily within our soft X-ray window. If modeled correctly,
we should expect that the $\beta$ component of our outer cluster
AGN+Stellar+BG+Halo model would account for little to no
hard X-ray flux.

In Section 3.3, we use a fixed 7 keV thermal bremsstrahlung
model to represent the spectrum of LMXBs. However, their
emission is expected to span a broad range in energy (e.g.,
0.3–8 keV; Boroson et al. 2011) and could potentially impact
the fit in the hard X-ray band.

Figure 7. Same as Figure 6, but for 4–8 keV data. All three models fit the SBP in both clustercentric radius bins equivalently well. This suggests that the AGN+Stellar+
+BG (AGN+Stellar+BG+Halo) model is an appropriate model of the hot halo emission in the soft X-rays in the inner (outer) cluster. Unlike at lower energy, the
AGN+BG models fit the hard X-ray data extremely well at all clustercentric radii, suggesting that an AGN and the cluster background are the primary sources of
4–8 keV emission.
Following the procedure described in Sections 3.4 and 3.5, we analyze the 4–8 keV SBPs of A1795 members. In the upper panels of Figure 7, we plot the measured hard X-ray SBPs, sampled model SBPs, and scaled PSFs. The relative residuals of the models are plotted in the lower panels. In this figure, we use the same color scheme as for the soft X-ray analysis.

As with the soft X-ray SBPs, the scaled PSF alone cannot account for the 4–8 keV flux. Qualitatively, however, the AGN + BG model fits the hard X-ray SBPs in both the inner and outer cluster, despite the large amount of scatter present in the data. In both clustercentric radius bins, the AGN + Stellar + BG model is consistent with the AGN + BG model. In the inner cluster, the addition of the LMXB component results in an increase in the reduced $\chi^2$ from 5.09 for the AGN + BG model to 5.63 for the AGN + Stellar + BG model. In the outer cluster, all three models fit the 4–8 keV SBPs equivalently well. Because of this, each additional component in the model worsens the reduced $\chi^2$. The AGN + BG model has a reduced $\chi^2$ of 1.75. With the addition of the LMXB component, the reduced $\chi^2$ rises to 1.84. Finally, the AGN + Stellar + BG + Halo model has the worst reduced $\chi^2$ of the three outer cluster models, with a value of 2.08.

This can be interpreted as the halo component adding no new information to the model fits at 4–8 keV. Hence, we are confident that the $\beta$ function is an appropriate choice for modeling any potential hot halo contribution to the 0.5–1.5 keV SBPs of stacked outer cluster A1795 members.

3.7. Soft X-Ray Luminosities of Model Components

While the AGN + Stellar + BG + Halo model provides a substantially better fit of the 0.5–1.5 keV SBP in the outer cluster, the quality of the fit alone does not tell us much about whether A1795 galaxies retain their hot halos.

In order to determine the luminosity of the hot halo (and other components), we use the entire post-burn-in set of parameters from our MCMC simulations to generate SBPs for each component in both models (AGN + Stellar + BG for the inner cluster and AGN + Stellar + BG + Halo for the outer cluster). The profiles are integrated to find the total flux contributed by each component, and the luminosity of each component is calculated. The probability distributions of the nonbackground components are shown in Figure 8. There are clear detections of all components in both clustercentric radius bins.

The LMXB components have similar probability distributions in the low- and high-clustercentric radius bins, which is unsurprising given that we use the inner cluster distribution of $A_1$ as a prior for the MCMC run in the outer cluster. This is justified, as the scaling between the X-ray and $i$ band should not vary based on location within the cluster.

Given our data and possible model components, we consider the AGN + Stellar + BG model to be the ideal representation of the soft X-ray SBP in the inner cluster. For completeness, however, we estimate the upper limit on any potential hot halo luminosity by taking the 90th percentile of the set of post-burn-in $\beta$ function parameters from the test run of the AGN + Stellar + BG + Halo model in the inner cluster (see the last paragraph in Section 3.5). This value, $L_{X,\text{halo}} = 1.3 \times 10^{39}$ erg s$^{-1}$, is plotted as the green vertical line in the upper panel of Figure 8. While the probability distribution of the hot halo component in the outer cluster has a peak near $10^{39}$ erg s$^{-1}$, it does have a nonnegligible probability tail that extends to a few $10^{39}$ erg s$^{-1}$. However, the minimum value in the outer cluster hot halo luminosity distribution is $L_{X,\text{halo}} = 1.7 \times 10^{39}$ erg s$^{-1}$, approximately 1.3 times larger than the upper limit of the inner cluster hot halo luminosity. Based on these two data points, there appears to be an environmental trend in the X-ray luminosity of A1795 galaxy hot halos.

![Figure 8. X-ray luminosity probability distributions of nonbackground components of the AGN + Stellar + BG model (inner cluster; upper panel) and the AGN + Stellar + BG model (outer cluster; lower panel). The green vertical line in the upper panel shows the estimated upper limit on hot halo luminosity. The X-ray luminosities are calculated from the parameter distributions that result from the MCMC simulations. The blue shaded region shows the expected $L_X$ due to LMXBs based on the stellar mass–$L_{X,\text{LMXB}}$ relation from Zhang et al. (2011). The red shaded region shows the expected $L_X$ due to LMXBs from Anderson et al. (2015), which they based on the $L_{X,\text{LMXB}}$–$L_X$ relation from Boroson et al. (2011). The LMXB X-ray luminosity derived through our MCMC simulations (red histograms) is consistent with both comparison LMXB X-ray luminosity ranges. The cyan shaded region shows the expected $L_X$ due to HMXBs from the SFR–$L_{X,\text{HMXB}}$ relation from Mineo et al. (2012). All X-ray luminosities presented here are in the 0.5–1.5 keV range.](image-url)
Table 1

| Component   | $L_X$ ($\times 10^{39}$ erg s$^{-1}$) |
|-------------|--------------------------------------|
| Total       | 1.8 ± 1.7                            |
| LMXB        | 1.6 ± 0.5                            |
| AGN         | 0.2–0.2                              |
| Hot halo    | <1.3                                 |
| Outer Cluster |                                       |
| Total       | 15.6 ± 2.6                           |
| LMXB        | 2.0 ± 0.5                            |
| AGN         | 5.4 ± 0.8                            |
| Hot halo    | 8.1 ± 3.5                            |

In Table 1, we present the nonbackground component luminosities for each model, the background-subtracted total luminosity (Total), and the upper limit to the hot halo luminosity for the inner cluster.

4. Discussion

4.1. Literature Comparison

4.1.1. Total and Component X-Ray Luminosity

As noted previously, the LMXB components of our models have similar luminosities in the inner and outer cluster regimes. While the LMXB component at $0.25 < R_{\text{clust}}/R_{500} < 1$ provides the dominant contribution to the total background-subtracted X-ray luminosity, LMXBs are the subdominant component in the outer cluster. In order to determine whether our values are reasonable, we use the stellar masses of our final sample and Equation (2) to find the expected range in 0.5–1.5 keV luminosity for the LMXBs in both clustercentric radius bins (shown in Figure 8 with the blue shaded regions). Furthermore, Anderson et al. (2015) provided expected LMXB luminosities based on the $L_X$,$L_{\text{LMXB}}$–$L_X$ relation from Boroson et al. (2011). Converting their published $L_X$ values to the 0.5–1.5 keV band, we plot these with the red shaded regions in Figure 8 for the stellar mass range of our final sample. This is remarkable consistency between these different estimates of LMXB luminosity.

The cyan shaded regions in Figure 8 show the expected 0.5–1.5 keV luminosity due to HMXBs from Equation (1), based on the SFRs of our final sample. This further exemplifies that HMXBs are not expected to provide a substantial contribution to the SBPs of A1795 members and supports their exclusion from our models.

Anderson et al. (2015) provided total galaxy X-ray luminosities (0.5–2.0 keV) for “locally brightest” SDSS galaxies, binned by stellar mass. In order to compare these to our background-subtracted $L_X$ values, we find the mean stellar mass of our inner and outer cluster samples with uncertainties on the mass derived through 10,000 iterations of bootstrap resampling with replacement. In the inner (outer) cluster, the log of the mean stellar mass is $\log(M_*/M_\odot) = 10.48 ± 0.05$ ($\log(M_*/M_\odot) = 10.67^{+0.09}_{-0.11}$). For our inner cluster galaxies, the luminosity of the corresponding mass bins from Anderson et al. (2015) spans the range $7.2 \times 10^{38} < L_X,\text{Total}/\text{erg s}^{-1} < 3.1 \times 10^{39}$, while the range for the bins that overlap with our outer cluster stellar mass is $3.1 \times 10^{39} < L_X,\text{Total}/\text{erg s}^{-1} < 9.9 \times 10^{40}$. These luminosities are corrected for the difference in energy ranges using WebPIMMS, assuming a compound model of a 1 keV thermal bremsstrahlung for the hot gas, 7 keV thermal bremsstrahlung for LMXBs, and a power law with a photon index of 2 for the AGN and HMXB emission. We do not consider the uncertainties published by Anderson et al. (2015), although these would only serve to widen the luminosity ranges.

Kim & Fabbiano (2013) measured 0.3–8 keV luminosities of nearby gas-poor early-type galaxies. Following the same procedures as with the Anderson et al. (2015) luminosities, we convert the Kim & Fabbiano (2013) values to our soft X-ray energy band and find that they span the range $1.1 \times 10^{39} < L_X,\text{Total}/\text{erg s}^{-1} < 5.4 \times 10^{39}$. This range is consistent with our inner cluster background-subtracted luminosity of $L_X,\text{Total} = (1.8 ± 1.7) \times 10^{39}$ erg s$^{-1}$. Given that these galaxies have at most negligible hot halo emission (on average), this consistency is to be expected. Outer cluster A1795 members, on the other hand, have a relatively strong hot halo component, so we would not expect their total luminosity ($L_X,\text{Total} \sim 2 \times 10^{40}$ erg s$^{-1}$) to agree with those of gas-poor galaxies. A simple subtraction of the hot halo luminosity from the total for outer cluster galaxies gives a value that is also consistent with the results of Kim & Fabbiano (2013).

The overall consistency between these total $L_X$ values from the literature and our background-subtracted total X-ray luminosities is encouraging, as it suggests that our selection of a constant for the ICM was the correct one.

The X-ray luminosity of outer cluster AGNs ($L_X,\text{AGN} \sim 5 \times 10^{39}$ erg s$^{-1}$) is consistent with the range of AGN luminosities found by LaMassa et al. (2012) for Seyfert galaxies. While our AGN luminosity at $1 < R_{\text{clust}}/R_{500} < 2.5$ falls on the low end of this range ($2.5 \times 10^{39} \lesssim L_X,\text{AGN}/\text{erg s}^{-1} \lesssim 1.6 \times 10^{39}$; converted to the 0.5–1.5 keV band), it is likely that only a few of the 26 galaxies in this bin have strong AGN emission, as the fraction of AGNs in low-redshift clusters is small; Martini et al. (2009) and Haines et al. (2012) both found X-ray–detected AGN fractions of <1% in 0.05 < z < 0.3 and 0.15 < z < 0.3 clusters, respectively. Even at high clustercentric radius, few cluster galaxies are expected to host AGNs (e.g., Lopes et al. 2017 found an AGN fraction of ~5% for RR/200 > 1 galaxies in z < 0.11 clusters).

While AGNs provide a substantial component of the X-ray luminosity at large clustercentric radius, they are clearly subdominant for low clustercentric radius galaxies ($L_X,\text{AGN} \sim 2 \times 10^{38}$ erg s$^{-1}$). Their X-ray luminosity is an order of magnitude lower than that of LMXBs and even lower than the upper limit of hot halo luminosity. The large difference in AGN $L_X$ as a function of clustercentric radius is unsurprising, as the AGN fraction tends to increase with clustercentric radius (e.g., Ehler et al. 2014; Lopes et al. 2017).

4.1.2. Hot Halos Around A1795 Galaxies

In Figure 9, we plot the 0.5–1.5 keV luminosity (upper limit) of the hot halo component of our AGN+Stellar+BG +Halos (AGN+Stellar+BG+Halos) model at the mean stellar mass found in Section 4.1.1. We compare our values to a selection of hot halo luminosities from the literature for field and cluster galaxies (see legend). Here we briefly describe the comparison samples. The reader is encouraged to refer to the cited papers for further details. For all comparison samples, we convert their published $L_X$ values to stellar masses using the K-band stellar mass-to-light ratio from Bell et al. (2003),

Wagner, McDonald, & Courteau

AGN LXB 2.0

LX Component - Total 1.8

Hot halo

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Figure 9. Soft X-ray (0.5–1.5 keV) hot halo luminosity vs. galaxy stellar mass. The green point (vertical error bar) shows the median (15th to 85th percentile) X-ray luminosity of the hot halo of outer cluster members of A1795. The downward-pointing green arrow represents the estimated upper limit of the hot halo of inner cluster A1795 members. Both of our values are plotted at the mean stellar mass of the galaxies in the stack, and the horizontal error bars are the standard error on the mean stellar mass of the stacked galaxies derived through 10,000 iterations of bootstrap resampling. The short vertical lines at the bottom of the plot show the mass range of A1795 members. Other points represent a selection of hot halo luminosities from the literature scaled to the 0.5–1.5 keV band. The red points are for cluster galaxies, while the blue points are for galaxies in the field. Lighter-colored red and blue points with downward-pointing arrows represent upper limits.

We include hot halo luminosities from Goulding et al. (2016) for galaxies from the MASSIVE survey (Ma et al. 2014). For these galaxies, Goulding et al. (2016) included the number of nearby neighbors for each. We separate their galaxies into two samples: those that have at least five neighbors (their classification for rich groups and clusters) are considered group/cluster galaxies, and galaxies with fewer than five neighbors are considered field galaxies.12 We remove the group/cluster galaxies that they classify as either being the central in their potentials or hosting an AGN. We also include a subset of lower-mass ATLAS3D (Cappellari et al. 2011) galaxies that Goulding et al. (2016) published as a comparison sample. We select galaxies that were also studied by Su et al. (2015) and use their classifications to separate them: galaxies that are listed as a Virgo cluster member, have at least 15 nearby SDSS neighbors, or were defined as a group/cluster galaxy in the literature are considered cluster galaxies, and all others are considered field galaxies. The comparison cluster/group (field) galaxies from Goulding et al. (2016) are shown with red (blue) diamonds.

At 0.25 < \( R_{\text{clust}} / R_{500} < 1 \), A1795 galaxies have a stacked \( L_{X,\text{halo}} \) upper limit almost uniformly lower than all other cluster galaxies plotted. Clearly, hot halos with low X-ray luminosity do exist in the cluster environment, but there appears to be a

12 Increasing the cutoff to 15 neighbors had no impact on the sample.
lack of cluster galaxies with \( \log (M_{*}/M_\odot) \lesssim 10.8 \) that host hot halos with low field-relative \( L_{X,\text{halo}} \). This could be due to observational biases: cluster galaxies are embedded in the ICM, making individual detections of very low X-ray luminosity hot halos nearly impossible. Observations of field galaxies are not subject to this high background, making hot halo detections easier. Another possible cause of the paucity of low-luminosity hot halos around lower-mass cluster galaxies is that they are unable to hold onto their tenuous halo gas when traveling through the ICM.

While we do not have a formal detection of \( L_{X,\text{halo}} \) for the inner cluster, by stacking 32 galaxies with 3.4 Ms of Chandra coverage, we are able to make measurements not typically possible for individual cluster galaxies. Our low clustercentric radius hot halos have a stacked X-ray luminosity upper limit that is consistent with the lowest values plotted for field galaxies.

If the true inner cluster \( L_{X,\text{halo}} \) value is somewhat near its upper limit, there are two broad possibilities for the distribution of individual hot halo luminosities: most (or all) of the galaxies in the inner cluster could have some small residual amount of hot halo gas, or a few members may possess a relatively large amount of hot halo gas. However, due to the small number of galaxies in our sample and the coarseness of our binning, determining which, if any, of these two scenarios is beyond the scope of this work.

In the outer cluster, A1795 galaxies have hot halo luminosities consistent with the comparison samples around the same stellar mass. These galaxies have almost uniformly higher \( L_{X,\text{halo}} \) than field and cluster galaxies with \( 10 < \log (M_{*}/M_\odot) \lesssim 10.5 \) and toward the upper envelope in luminosity for galaxies at \( 10.5 \lesssim \log (M_{*}/M_\odot) \lesssim 11.3 \). Given that our hot halo luminosity is the average for 26 galaxies over both of these mass ranges, these results suggest that A1795 galaxies beyond \( R_{500} \) have large hot gas halos.

While massive cluster galaxies appear to hold onto their hot halos more readily than their less massive cluster counterparts, the highest-mass (\( \log (M_{*}/M_\odot) \gtrsim 11.1 \)) field galaxies have almost uniformly higher hot halo X-ray luminosities than the most massive cluster galaxies. However, since field galaxies are not subject to the ram pressure of an ICM, it is unsurprising that they can build up larger hot gas reserves. Hence, these differences in the hot halo X-ray luminosity of field and cluster galaxies at large stellar mass are likely due to environmental effects, while at lower stellar mass, the exact cause may be a combination of environment effects and observation biases.

4.2. Implications on the Quenching of Cluster Galaxies

We have shown, based on their hot halo X-ray luminosities, that A1795 members are a dichotomous population. On average, galaxies within \( R_{500} \) retain little to none of their hot halo gas. Outer cluster galaxies have substantially more luminous hot halos, with X-ray luminosities a factor of six larger than the upper limit of the inner cluster \( L_{X,\text{halo}} \) (see Table 1 and Figure 9). With only two very large clustercentric radius bins, we cannot determine the radial trend with any accuracy; however, it is likely that we are observing the removal of hot halos as galaxies fall into A1795. Taken on its own, this is evidence for ongoing strangulation.

Given these results, a next step would be to investigate their implications on different quenching mechanisms. While an in-depth study of the stellar populations and cold gas content of A1795 members is beyond the scope of this work and would require more extensive photometry, we can further leverage the Chang et al. (2015) catalog. It provides specific SFRs (\( \text{sSFR} = \text{SFR}/M_* \)), which are commonly used to determine whether a galaxy is quiescent or star-forming. Adopting an sSFR cutoff of \( \log (\text{sSFR}/\text{Gyr}^{-1}) > -1 \) (e.g., Lin et al. 2014), we find that none of our galaxies are classified as star-forming. If we instead use a less conservative cut of \( \log (\text{sSFR}/\text{Gyr}^{-1}) > -1.5 \) (Genel et al. 2018; see their Figure A1 for \( 10 \lesssim \log (M_{*}/M_\odot) \lesssim 10.5 \) galaxies at \( z \sim 0.1 \)), two of our outer cluster galaxies are classified as star-forming; none of the inner cluster galaxies, however, make this more relaxed cut. This results in quiescent fractions of \( 1.0^{+0.1}_{-0.06} \) (32/32) and \( 0.92^{+0.05}_{-0.06} \) (24/26) for the inner and outer cluster, respectively. With only \( \sim 30 \) galaxies in each bin, the fractions are quite uncertain and formally consistent with each other, so we are unable to measure any radial trend.

Using the \( R_{300} \) for A1795 from Shan et al. (2015), we can convert our \( R/R_{300} \) to \( R/R_{500} \) values and compare our quiescent fractions to those of Wetzel et al. (2012), who measured the quiescent fraction as a function of \( R_{200} \) for \( z \sim 0.045 \) galaxies in \( \log (M_{\text{halo}}/M_\odot) > 14 \) halos (their Figure 5). In terms of \( R_{200} \), our inner cluster galaxies span \( 0.15 \lesssim R/R_{200} \lesssim 0.61 \). Over this range, our fraction is comparable to the values plotted by Wetzel et al. (2012), being consistent with two of their \( \sim 6 \) binned fractions. At large clustercentric radius (\( 0.61 \lesssim R/R_{200} \lesssim 1.51 \)), the situation is similar, with our fraction consistent with one of their \( \sim 4 \) binned values.

A galaxy that no longer possesses a hot halo yet is still actively star-forming would be strong evidence for ongoing strangulation. However, the nature of this work precludes such a discovery. While we can identify at most two galaxies in the outer cluster that are still forming stars, given our method for measuring the X-ray luminosities of model components, we cannot determine the individual strengths of these galaxies’ hot halos. Even though most, if not all, A1795 members are quiescent, we can still begin to broadly investigate some of the possible quenching mechanisms at play.

Since none of the inner cluster members are still forming stars, this is actually evidence against ongoing strangulation. However, it is possible that members had their hot halos stripped but retained a portion of their cold gas when they entered the cluster environment. That cold gas could have been subsequently consumed as the galaxies made their way to the inner cluster. This scenario is supported by the results of Zinger et al. (2018), who found that RPS is not an effective mechanism for removing gas from galactic disks in cluster outskirts.

The ineffectiveness of RPS at large clustercentric radius would also suggest that ram pressure is likely not the cause of the quiescence of the outer cluster members. Additionally, the galaxies in the outskirts of A1795 still have, on average, substantial hot halos, so ram pressure may not yet be strongly affecting them. However, inner cluster members have negligible hot halos, which may indicate that RPS has effectively removed the majority of the hot halo gas and cold interstellar gas. Since ram pressure is proportional to the square of a galaxy’s velocity, the effects of RPS will likely be stronger near the centers of clusters, where galaxies are traveling more quickly through the ICM.
Given the high X-ray luminosity of the AGN component in our model at large clustercentric radius, quenching due to an AGN may be a possibility. As we noted in Section 4.1.1, though, only a handful of cluster galaxies, even in the outskirts, are likely to host an AGN, so AGN quenching on a large scale in A1795 is unlikely. With its large mass \((M_{500} = 5.46 \times 10^{14} M_\odot)\), A1795 would not be a conducive environment for galaxy–galaxy interactions, which tend to favor regions with low galaxy velocities. Some A1795 members at large clustercentric radius have likely been recently accreted from lower-density (group) environments, where tidal interactions between galaxies are more common. It would seem that regardless of the dominant quenching mechanism, a substantial fraction of the quiescent galaxies, particularly at large clustercentric radius, may have arrived in the cluster prequenched (preprocessing).

5. Summary

In this paper, we model the stacked, soft (0.5–1.5 keV) X-ray emission of spectroscopic member galaxies in A1795. We model the extended stacked emission using a combination of spatially flat background cluster emission, central component from an AGN, extended emission from a stellar component (i.e., LMXBs), and an additional extended component corresponding to the diffuse hot halo associated with individual galaxies.

As an ensemble, galaxies interior to \(R_{500}\) have total (i.e., background-subtracted) soft X-ray luminosities that are consistent with nearby gas-poor early-type galaxies. In contrast, galaxies exterior to \(R_{500}\) are 3–14 times brighter in the X-ray than those of the comparison sample. With a 0.5–1.5 keV luminosity of \(L_{X,\text{halo}} = (8.1^{+5.3}_{-3.5}) \times 10^{40} \text{ erg s}^{-1}\), extended hot halos have been detected around A1795 members exterior to \(R_{500}\) in a statistical sense. This hot halo luminosity also accounts for the difference in total luminosities between the outer cluster members and the comparison gas-poor early-type galaxies. While hot halos provide a significant component of the X-ray emission of outer cluster members, we find that they are clearly subdominant in the inner cluster, where we calculate an upper limit of \(L_{X,\text{halo}} < 1.3 \times 10^{40} \text{ erg s}^{-1}\).

Such a large difference in the X-ray luminosity of extended gas halos around member galaxies interior and exterior to \(R_{500}\) suggests that we are witnessing the stripping of hot halos from A1795 members as they travel through the dense ICM. On its own, this result would support quenching by ongoing strangulation. However, all of the inner cluster members are already quiescent according to their sSFRs, so at most we can suggest that they were quenched by strangulation. While outer cluster members, on average, still possess their hot halos, nearly all are quiescent. This quenching was likely caused before the galaxies entered the cluster environment, with the removal of the hot halo preventing the “reignition” of star formation in the future. Preprocessing is the preferred quenching explanation, as AGN activity and galaxy–galaxy interactions are unlikely to quench on a large scale in A1795, and RPS would not strip the cold gas and leave the more tenuously bound hot halo.

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