The Luminous X-Ray Halos of Two Compact Elliptical Galaxies

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Abstract

There is mounting evidence that compact elliptical galaxies (CEGs) are local analogs of the high-redshift “red nuggets” that are thought to represent progenitors of today’s early-type galaxies (ETGs). We report the discovery of extended X-ray emission from a hot interstellar/intragalactic medium in two CEGs, Mrk 1216 and PGC 032873, using shallow Chandra observations. We find that PGC 032873 has an average gas temperature of \( k_B T = 0.67 \pm 0.06 \) keV within a radius of 15 kpc and a luminosity \( L_x = (1.8 \pm 0.2) \times 10^{51} \) erg s\(^{-1}\) within a radius of 100 kpc. For Mrk 1216, which is closer and more luminous \((L_x(<100 \text{ kpc}) = (12.1 \pm 1.9) \times 10^{51} \) erg s\(^{-1}\)), we used an entropy-based hydrostatic equilibrium (HE) procedure and obtained a good constraint on the \( H \)-band stellar mass-to-light ratio, \( M_{\text{stars}}/L_H = 1.33 \pm 0.21 \) solar, that is in good agreement with stellar dynamical (SD) studies, which supports the HE approximation. We obtain a density slope of 2.22 ± 0.08 within \( R_e \) that is consistent with other CEGs and normal local ETGs, while the dark matter fraction within \( R_e \), \( f_{\text{DM}} = 0.20 \pm 0.07 \) is similar to local ETGs. We constrain the supermassive black hole mass, \( M_{\text{BH}} = (5 \pm 4) \times 10^9 \) \( M_\odot \), with \( M_{\text{BH}} > 1.4 \times 10^{10} \) \( M_\odot \) (90% confidence), which is consistent with a recent SD measurement. We obtain a halo concentration \( c_{200} = 17.5 \pm 6.7 \) and mass \( M_{200} = (9.6 \pm 3.7) \times 10^{14} \) \( M_\odot \), where \( c_{200} \) exceeds the mean \( \Lambda \)CDM value (\( \approx 7 \)), which is consistent with a system that formed earlier than the general halo population. We suggest that these galaxies should be classified as fossil groups.

Key words: galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: groups: general – galaxies: individual (Mrk 1216, PGC 032873) – X-rays: galaxies

1. Introduction

Over the past decade, it has become increasingly clear that most early-type galaxies (ETGs) form and evolve via a two-stage process (e.g., Oser et al. 2010). Initially, the galaxy collapses and rapidly evolves through strong dissipation and wet mergers assembling most of its stellar mass and becomes a “red nugget” by \( z \approx 2 \). Compared to the present-day ETG population, red nuggets are much more compact and have disky isophotes that are consistent with being fast rotators. The second phase of the ETG evolution is a gradual build-up of its stellar envelope around the core red nugget through mostly dry mergers and the passive evolution of its stellar population. This is reflected in the well-established size-mass evolution of ETGs (e.g., van Dokkum et al. 2008) and through multi-component decompositions of nearby ETGs (Huang et al. 2013). Unfortunately, because red nuggets exist at high redshift, it has not been possible yet to measure radial mass profiles in detail to probe more effectively the first phase.

A new way to approach studying red nuggets in more detail is through local analogs. There is mounting evidence that compact elliptical galaxies (CEGs; e.g., van den Bosch et al. 2015) are indeed largely untouched, passively evolved descendants of the high-redshift red nuggets. The CEGs possess many of the same basic properties (e.g., small size, large stellar mass, etc.), but only a relatively small number of CEGs have been studied in detail. In the largest and most comprehensive study to date, Yildirim et al. (2017, hereafter Y17) present stellar dynamical models of integral field unit (IFU) kinematic data along with stellar populations studies of 16 CEGs. Three of these have also been studied recently by Ferré-Mateu et al. (2017) in detail, confirming their identification as “massive relic galaxies” (MRGs). Yildirim et al. (2017) find that, within 1 \( R_e \), both the total mass slope and the mean stellar mass fraction are higher than present-day ETGs. They argue that both of these properties are consistent with a dissipative formation for the red nuggets. Y17 also argue their analysis of the CEGs disfavors adiabatic contraction of their dark matter (DM) halos, which would represent an important constraint on the ubiquity of that evolutionary process (e.g., Blumenthal et al. 1986; Gnedin et al. 2004; Dutton et al. 2015).

Finally, CEGs/MRGs have generated significant interest since several studies suggest that they possess supermassive black holes (SMBHs) that are positive outliers (i.e., overmassive) at the high-mass end \((>10^9 \) \( M_\odot \)) of the BH-mass scaling relations (e.g., Ferré-Mateu et al. 2015; van den Bosch et al. 2015; Walsh et al. 2015; Yildirim et al. 2016; Walsh et al. 2017), similar to those BHs found in some brightest cluster galaxies (e.g., McConnell et al. 2012; Rusli et al. 2013; Thomas et al. 2016).

What has been learned so far for the mass profiles has been achieved only through stellar dynamics. These systems are too nearby for studies with gravitational lensing. However, they are potentially ideal sites for hydrostatic equilibrium (HE) studies of their hot gas, given that they are believed to be largely untouched, passively evolved descendants of the high-redshift universe. HE allows the gravitating mass to be derived directly from the temperature and density profiles of the interstellar medium (ISM), from the center to the halo outskirts using a single dynamical tracer.

In this paper, we describe a search for promising CEG/MRG targets to apply the HE approach to study the mass profiles to complement and augment what has and is currently being learned from stellar dynamics. In Section 2, we identify the CEG sample in which we searched for targets with extended X-ray emission suitable for HE analysis from which we identify two promising galaxies, Mrk 1216 and PGC 032873.
We describe the Chandra X-ray observations and data preparation in Section 3. We define the models used for spectral analysis in Section 4. In Section 5, we present results for PGC 032873. For Mrk 1216, we describe the models and results in Section 6. We present an analysis of the image properties in Section 6.1 and the results of the spectral analysis in Section 6.2. The HE models are presented in Section 6.3 and the results in Section 6.4. We present our conclusions in Section 7.

2. CEG Sample

We searched for promising CEG targets for an HE study of their hot ISM using the new catalog of Y17, which presents stellar dynamical studies of 16 nearby CEGs. We summarize the results of our initial survey of X-ray data archives as follows:

1. No Chandra or XMM-Newton data—NGC 384, NGC 472, NGC 2767, and PGC 70520
2. Nucleon point sources with little extended emission—UGC 2698 and UGC 3816
3. ULX (Walton et al. 2011) with little extended emission—NGC 3990
4. Negligible/insufficient diffuse emission—PGC 011179, PGC 12562, and NGC 1282
5. Perseus cluster galaxies for which determining the extended nature of emission is problematic due to the source being far off-axis, on a chip edge, and/or swamped by intracluster medium—NGC 1270, NGC 1271, NGC 1277, and NGC 1281
6. Isolated galaxies with luminous, extended X-ray emission—Mrk 1216 and PGC 032873

Unfortunately, most of the CEGs in the Y17 catalog are not promising for study presently for a variety of reasons. Some lack any Chandra or XMM-Newton data to search for extended emission. Most of the targets do not show clear evidence for substantial extended emission with the existing data. However, two targets are very promising for an HE study of extended X-ray emission: (1) Mrk 1216 and (2) PGC 032873. Both of these objects are recently very well-studied in optical/infrared (IR), confirming their status as MRGs (Ferré-Mateu et al. 2017; Yıldırım et al. 2017) and possibly with over-massive SMBHs (e.g., Ferré-Mateu et al. 2015; Walsh et al. 2017). We list their basic properties in Table 1 and then analyze in detail their extended X-ray emission.

| Name           | Redshift | Distance (Mpc) | Scale (kpc/arcsec) | N_H (10^{20} cm^{-2}) | L_{50} (10^{43} L_{\odot}) | R_e (kpc) | \sigma_e (km s^{-1}) | L_x (10^{41} erg s^{-1}) | k_B T (keV) |
|----------------|----------|----------------|--------------------|------------------------|-----------------------------|-----------|----------------------|-----------------------------|-------------|
| Mrk 1216       | 0.021328 | 97.0           | 0.45               | 4.0                    | 1.14                        | 2.3       | 308                  | 12.1 \pm 1.9                | 0.76 \pm 0.02 |
| PGC 032873     | 0.024921 | 108.5          | 0.50               | 1.2                    | 1.21                        | 1.7       | 304                  | 18.0 \pm 0.2                | 0.67 \pm 0.06 |

Note. The redshift is taken from NASA/IPAC Extragalactic Database (NED: http://ned.ipac.caltech.edu). We compute the distance in our assumed cosmology using the redshift (also taken from NED) corrected to the reference frame defined by the 3K background. We calculate the Galactic column density using the HEASARC w3NHT tool, based on the data of Kalberla et al. (2005). The total IR luminosities and circumburst effective radii (R_e) are taken from Y17 for Mrk 1216 (H band) and from 2MASS for PGC 032873 (K band). The stellar velocity dispersions within R_e are taken from Y17 for both systems. L_x is the bolometric (0.1–50.0 keV) luminosity computed using the best-fitting hydrostatic model for each galaxy within an extrapolated projected radius of 100 kpc (Section 6.4). The temperatures are average values computed within 73 kpc for Mrk 1216 (Section 6.2) and 14.1 kpc for PGC 032873 (Section 5).

Table 1

Target Properties

Table 2

Observations

| Galaxy  | Obs. ID | Obs. Date | Instrument | Exposure (ks) |
|---------|---------|-----------|------------|---------------|
| Mrk 1216 | 17061   | 2015 Jun 12 | ACIS-S     | 12.8          |
| PGC 032873 | 17063     | 2015 Mar 2 | ACIS-S     | 22.7          |

Note. The exposure times refer to those obtained after filtering the light curves, which for each galaxy resulted in > 1 ks of excluded time.

3. Observations and Data Preparation

In Table 2, we list details of the Chandra observations of Mrk 1216 and PGC 032873. Unless stated otherwise, the data were prepared as described in Buote (2017, hereafter B17), and we refer the reader to that paper for further details. We used the Chandra Interactive Analysis of Observations (CIAO v4.9) and HEASOFT (v6.18) software suites, along with version 4.7.5.1 of the Chandra calibration database, to prepare the data for imaging and spatially resolved spectral analyses. For the imaging analysis, we extracted images from the cleaned events lists with energies 0.5–7.0 keV and employed 1.7 keV monochromatic exposure maps.

For the spectral analysis, we required a minimum 200source counts for each concentric circular annulus. In the case of PGC 032873, this resulted in only a single aperture (R = 30″= 15.1 kpc). We also included a larger annulus (R = 30″–150″) to help constrain the background. For Mrk 1216, our criterion resulted in 7 annuli (see Table 3) extending out to 73 kpc (2/7), plus a larger annulus (2/7–4/1) for aiding background constraints.

We also examined the likelihood that enhanced Solar Wind Charge Exchange (SWCX) emission significantly impacted the observations. We obtained the solar proton flux below \( \approx 2 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \), indicating significant proton flare contamination is not expected (Fujimoto et al. 2007).

4. Spectral Models

We performed frequentist fits of the plasma and background emission models to the spectra using XSPEC v12.9.0s (Arnaud 1996). We chose to minimize the C-statistic (Cash 1979) since it is largely unbiased compared to \( \chi^2 \) (e.g., Humphrey et al. 2009b). We modeled the hot ISM with the VAPEC

http://www.srl.caltech.edu/ACE/ASC/level2/sweswi_l3desc.html
plasma emission model and the cosmic and particle backgrounds with a combination of power laws and Gaussians. For both galaxies, the unresolved Low-Mass X-Ray Binary (LMXB) contribution is unimportant, and we modeled it as a 7.3 keV thermal bremsstrahlung component (e.g., Matsumoto et al. 1997; Irwin et al. 2003) with the normalization fixed by the $L_{\text{X}} - L_K$ scaling relation for unresolved discrete sources of Humphrey & Buote (2008), using the $K$-band luminosity listed in Table 1. The hot ISM components are allowed to vary between the annuli while the background components are tied. For each galaxy, the background models are also fitted in the extra large annulus (Section 3), which provides the key constraints on the background. We refer the reader to Section 3 of B17 for details on the models and fitting procedure.

For Mrk 1216, we found the soft Cosmic X-Ray Background (CXB) components fitted to negligible fluxes with large errors. Consequently, for that galaxy, we fixed the soft CXB normalizations to those obtained from fitting Röntgen-Satellite ROSAT data using the HEASARC X-ray Background\(^{3}\) Tool.

5. PGC 032873

In Figure 1, we display the image overlaid with contours for the central region ($\approx 15''$) of PGC 032873. Although the number of source counts is small (only $\approx 170$ within the displayed circle), extended emission centered on the stellar light is clearly observed. The morphology of the X-ray isophotes is broadly consistent with that of the $H$-band image reported by Y17, i.e., isophotal ellipticity 0.53 and position angle 42°. (In Figure 1 North is up and East is to the left).

In Figure 1, we also plot the spectrum and best-fitting model in a circular aperture with radius $R = 30'' = 15.1$ kpc containing $\approx 200$ source counts. The temperature of the hot ISM within the aperture is well constrained: $k_B T = 0.67 \pm 0.06$ keV with a subsolar (though less certain) metallicity, $Z = 0.42 \pm 0.23 Z_{\odot}$. The best-fitting aperture luminosity is $L_{\text{X}} = 6.8 \times 10^{40}$ erg s$^{-1}$ (0.5–7.0 keV). These properties are indicative of a typical X-ray luminous massive elliptical galaxy (e.g., Humphrey et al. 2006) e.g., using the mass-temperature scaling relation of galaxy groups from Lovisari et al. (2015) gives $M_{200} = 2 \times 10^{13} M_{\odot}$.

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\(^{3}\) https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/xraybg/xraybg.pl

Table 3

| Annulus | $R_{\text{in}}$ (kpc) | $R_{\text{out}}$ (kpc) | $\Sigma_{\text{X}}$ (0.5–7.0 keV) (erg cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$) | $k_B T$ (keV) | $Z$ (solar) |
|---------|-----------------------|------------------------|-------------------------------------------------|---------------|-------------|
| 1       | 0.00                  | 0.78                   | 3.06e+01 $\pm$ 1.21e+11                         | 1.026 $\pm$ 0.041 | 1.04 $\pm$ 0.58 |
| 2       | 0.78                  | 1.77                   | 9.00e+01 $\pm$ 3.81e+12                         | 0.809 $\pm$ 0.046 | tied        |
| 3       | 1.77                  | 3.54                   | 2.52e+02 $\pm$ 1.08e+12                         | 0.785 $\pm$ 0.041 | tied        |
| 4       | 3.54                  | 6.86                   | 8.55e+02 $\pm$ 2.57e+13                         | 0.725 $\pm$ 0.040 | 0.65 $\pm$ 0.34 |
| 5       | 6.86                  | 14.38                  | 2.34e+03 $\pm$ 7.28e+14                         | 0.624 $\pm$ 0.038 | tied        |
| 6       | 14.38                 | 28.77                  | 5.15e+03 $\pm$ 1.98e+14                         | 0.720 $\pm$ 0.059 | 0.38 $\pm$ 0.21 |
| 7       | 28.77                 | 73.03                  | 6.78e+03 $\pm$ 2.68e+15                         | 0.609 $\pm$ 0.117 | tied        |

Note. 1 kpc = 200.22. Annuli where the metallicity is linked to the value in the previous annulus are indicated as “tied.” Note that the definition of $\Sigma_{\text{X}}$ is essentially the emission measure (i.e., XSPEC NORM parameter, which is the parameter actually fitted to the spectral data) multiplied by the plasma emissivity divided by $\pi \theta^2$ (arcmin$^2$), where $\theta$ is the aperture radius in arcminutes. Rather than quote the results for NORM itself, we have used the best-fitting plasma emissivity for each annulus (i.e., the plasma emissivity evaluated using the best-fitting $k_B T$ and metallicity $Z$) to convert NORM into a surface brightness unit. Consequently, the error bars quoted for $\Sigma_{\text{X}}$ are directly proportional to the error bars for NORM.

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Figure 1. Image and spectrum of PGC 032873. Left panel: Chandra image (0.5–7.0 keV, 0″/492 pixels) with contours overlaid with square-root spacing. Also shown is a circle of radius 15″ = 7.5 kpc for scale. Note this is the raw image used only for display purposes, i.e., no exposure correction or background subtraction has been applied. Right panel: Chandra spectrum extracted within a radius of 30″. The best-fitting spectral model is shown: hot gas + unresolved discrete sources (LMXBs) + CXB (green), the particle background (blue), and the total model (red).
Since the data are insufficient for a spectral analysis in multiple apertures, we also estimate the radial mass profile using the surface brightness profile and approximating the gas as isothermal. In Figure 2, we show the 0.5–7.0 keV radial surface brightness profile out to a radius of 3’. We fitted a model to the surface brightness consisting of (1) an isothermal $\beta$ model (Cavaliere & Fusco-Femiano 1978) for the hot gas; (2) a de Vaucouleurs model following the K-band light (Table 1) normalized as described in Section 4 to represent the unresolved LMXB component; and (3) two constant background components, one of which represents the particle background and is not corrected with the exposure map.

The composite model is a good fit to the surface brightness profile and yields for the $\beta$ model a core radius $R_e = 0.6\pm0.3$, slope parameter $\beta = 0.5^{+0.03}_{-0.02}$, and best-fit central density, $\rho_{gas,0} = 9.5 \times 10^{-25}$ g cm$^{-3}$. Assuming HE and using these best-fitting parameters along with the temperature and metallicity obtained for the spectrum quoted above, the best-fit $\beta$ model profile yields a total mass, $M_{500} = 1.3 \times 10^{13} M_\odot$, which is very consistent with the value obtained above from a scaling relation when considering the large statistical uncertainties.

6. Mrk 1216

6.1. Image Properties

We show the 0.5–7.0 keV Chandra image of the central $\sim 15''$ of Mrk 1216 in Figure 3 with contours overlaid. Like PGC 032873, the X-ray image of Mrk 1216 shows its emission is clearly extended and is centered on the peak of the stellar light. The displayed region contains $\approx 750$ source counts, allowing for a more detailed analysis than was possible for PGC 032873. After identifying point sources with the CIAO WAVDETECT tool, we replaced them with local background using the CIAO DMFILTH tool. We then computed the ellipticity and position angle of the surface brightness brightness as a function of semimajor axis using an iterative moment technique equivalent to diagonalizing the moment of inertia tensor (Carter & Metcalfe 1980; see Buote & Canizares 1994 for its application to X-ray images of elliptical galaxies).

Within the displayed region the X-ray position angle (PA, measured N through E) is consistent with following the $H$-band stellar light reported by Y17 (70°5), while the ellipticity is smaller than the $H$-band value ($\epsilon = 0.42$); e.g., for semimajor axis $10''$, we obtain $\epsilon = 0.24 \pm 0.07$ and PA = 71° ± 11°. The rounder X-ray isophotes compared to the stars suggests that the X-ray emission follows the gravitational potential, obeying approximate HE. This is further supported by the lack of any centroid variation.

To search for image irregularities in more detail, we used the CIAO package SHERPA to fit a circular $\beta$ model to the image and subtract the best-fitting model, yielding the residual image shown in the right panel of Figure 3. (Note that for this calculation, the image was first corrected with a 1.5 keV monochromatic exposure map. However, we found that the results were affected negligibly whether or not the exposure correction was applied.) We do not find any statistically significant features in the residual image. Hence, with the present data, the X-ray emission of Mrk 1216 appears to be very regular and to be consistent with a relaxed system.

6.2. Spectral Analysis

We obtain a good joint fit to the spectra in the seven annuli with a minimum C-statistic of 318 for 289 degrees of freedom (dof). The $\chi^2$ value for this fit is 312, yielding a null hypothesis probability of 17% for a formally acceptable fit. The good quality of the global fit is apparent in Figure 4 where we show the best-fitting model over-plotted on the spectra in two of the annuli.

In Table 3, we list the surface brightness ($\Sigma_\alpha$), temperature ($k_B T$), and the metallicity ($Z$) for the hot gas component in each annulus. The metallicity parameter is defined such that all the metal abundances other than iron are tied to iron in their solar ratios, where we use the solar abundance table of Asplund et al. (2006). The radial profiles of $\Sigma_\alpha$ and $k_B T$ are plotted in Figure 5.

The temperature declines from a maximum value of $\approx 1$ keV in the central radial bin to $\approx 0.6$ keV in the outermost aperture in a manner very similar to the temperature profile of NGC 6482 (B17). The source emission in the central bin where the temperature peaks is well described by thermal plasma emission. We found no evidence for spectrally hard nonthermal emission in the central bin when adding a power-law component potentially associated with the weak radio source detected in the NVSS (Condon et al. 1998). (Because in Section 7 we will have use of the average temperature, when tying $k_B T$ for all the apertures we obtain $k_B T = 0.76 \pm 0.02$ keV).

The metallicity is consistent with a significant negative radial gradient; i.e., $Z$ declines from $Z \approx 1 Z_\odot$ at the center to $Z \approx 0.4 Z_\odot$ in the outer radial bin similar to NGC 6482 (B17), NGC 5044 (Buote et al. 2003) and other massive elliptical galaxies and small groups (e.g., Buote 2000a; Humphrey & Buote 2006; Mernier et al. 2017). While the data are consistent with the metallicity gradient, it is not required. A fit of similar quality is obtained for a constant $Z = 0.73^{+0.23}_{-0.16} Z_\odot$. The statistical errors on the iron abundance

Figure 2. 0.5–7.0 keV radial surface brightness profile and best-fitting model for PGC 032873 (see Section 5). The vertical dotted line indicates the spectral extraction aperture at radius $R_{spec} = 30'' = 15.1$ kpc.
the ratios

Strongest statement that we can report regarding these is that in the Si, S focus our analysis on single-temperature models of the hot ISM to the Chandra projection of a radial temperature gradient applied. Right panel: residuals obtained after subtracting the best-circle of radius 15 kpc. The spatial fluctuations near the galaxy’s center are not statistically significant.

(which dominates the metallicity) are sufficiently large to render unimportant any Fe bias (e.g., Buote 2000b) from fitting a single-temperature model to a multi-temperature spectrum (such as that arising from the line-of-sight projection of a radial temperature gradient). We therefore focus our analysis on single-temperature models of the hot ISM in each annulus.

We also found that allowing other elements (i.e., O, Ne, Mg, Si, S) to vary separately from Fe resulted in little improvement in the fit and poorly constrained non-Fe abundances. The strongest statement that we can report regarding these is that the ratios $Z_{\text{Mg}}/Z_{\text{Fe}}$ and $Z_{\text{Si}}/Z_{\text{Fe}}$ are less than solar at 90% confidence.

6.3. Hydrostatic Equilibrium Models

We adopt a bayesian entropy-based procedure to fit spherical HE models of the hot ISM to the Chandra spectral data (Humphrey et al. 2008; see Buote & Humphrey 2012a for a review of this and other HE approaches). The biases associated with assuming spherical symmetry are small generally (e.g., Buote & Humphrey 2012b), and they are negligible in our present investigation relative to the large statistical errors on the fitted parameters. We refer the reader to B17 for details about the implementation of the method. Here we briefly summarize the fiducial model components used for Mrk 1216.

1. Entropy. The power law plus a constant, $S(r) = s_0 + s_1 r^\alpha$, where $S \equiv k_B T n_e^{2/3}$ is the entropy proxy expressed in units of keV cm$^2$, $r$ is expressed in kpc, and $s_0$, $s_1$, and $\alpha$ are free parameters. We also require, at some radius outside the data extent, that the logarithmic entropy slope match the value $\approx 1.1$ from cosmological simulations with only gravity (e.g., Tozzi & Norman 2001; Voit et al. 2005). We adopt a radius of 100 kpc for this purpose.

2. Pressure. The pressure boundary condition for the solution of the HE equation is a free parameter. We designate this “reference pressure” $P_{\text{ref}}$ to be located at a radius 10 kpc.

3. Stellar Mass. Multi-Gauss expansion (MGE) model of the HST H-band light reported by Y17. This stellar light profile is converted to stellar mass via the stellar mass-to-light ratio ($M_{\text{stars}}/L_{\text{H}}$), which is a free parameter in our model.

4. DM. Navarro–Frenk–White profile (NFW; Navarro et al. 1997) with free-parameters concentration and mass.

5. SMBH. We fix $M_{\text{BH}} = 4.9 \times 10^9 M_\odot$ to the stellar dynamical value (Walsh et al. 2017) for the fiducial HE model and discuss results obtained for other $M_{\text{BH}}$ values in Section 6.4.4.

Hence, our fiducial HE model has three free parameters for entropy, one for pressure, one for stellar mass, and two for the DM, i.e., a total of seven free parameters.

6.4. Results

6.4.1. Overview

We use a bayesian nested sampling procedure based on the MultiNest code v2.18 (Feroz et al. 2009) to fit the HE model to the Chandra data (see B17 for details). For the free parameters, we use flat priors except for $P_{\text{ref}}$ and $M_{\text{DM}}$, for which we adopt flat priors on their logarithms. The ranges of the priors were chosen to be large enough so that the best-fitting values were far from the boundaries as judged by the standard deviation of the parameter. The one exception to this is the NFW scale radius ($r_s$), for which the upper limit is poorly constrained. Consequently, we set the maximum value of the prior for $r_s$ to 50 kpc, representing essentially the average radius of the outer Chandra bin.

We quote two “best” values for each free parameter: “Best Fit,” the mean parameter value of the posterior; and “Max Like,” the parameter value that maximizes the likelihood. Errors quoted are the standard deviation (1σ) of the posterior.
Figure 4. Example Chandra spectra for Mrk 1216 in the 0.5–7.0 keV band without any background subtraction. Also plotted are the best-fitting models (red dashed) broken down into the separate contributions from the following: (1) hot gas and unresolved LMXBs from Mrk 1216 along with the CXB (green dotted-dashed), and (2) particle background (blue dotted).

unless stated otherwise. In Figure 5, we show the best-fitting fiducial model to the $\Sigma_\perp$ and $k_B T$ profiles and the fractional residuals. The fit is excellent as judged by the small fractional residuals. We have also performed a standard frequentist $\chi^2$ analysis to provide another means of judging the goodness-of-fit. This fit yields parameters extremely similar to the Max Like parameters of the bayesian fit and $\chi^2 = 5.3$ for 7 degrees of freedom (dof).

Omitting the stellar mass component gives $\chi^2 = 14.2$ for 8 dof; i.e., the Chandra data require the stellar mass component at the 99% level, according to the F-test. If instead the DM halo is omitted, then $\chi^2 = 65.7$ for 9 dof, showing that the Chandra data require it at the $\approx 4\sigma$ level. This X-ray evidence for DM in Mrk 1216 is noteworthy in light of recent stellar dynamical studies that yield conflicting results for the need for a DM halo based on near-IR data; i.e., Y17 do not require DM, while Walsh et al. (2017) do require it.

For reference, the best-fit virial radii are: $r_{2500} = 150 \pm 17$ kpc, $r_{500} = 295 \pm 38$ kpc, and $r_{200} = 429 \pm 56$ kpc. The extent of the data is $\approx r_{2500}/2$, which we indicate in Figure 6. Since the outer bin is large, the average bin radius $\approx 50$ kpc or $\approx r_{2500}/3$ is more relevant for the HE models.

6.4.2. Entropy

We plot the entropy profile in Figure 6 with the entropy scaled by $S_{500} = 46.1$ keV cm$^2$ (see Equation (3) of Pratt et al. 2010) and give the parameter constraints in Table 4. The entropy profile shape is similar to that of other massive elliptical galaxies (e.g., Humphrey et al. 2008, 2009a, 2011, 2012a; Werner et al. 2013; Buote 2017). Note the slope $\alpha$ is somewhat shallower than the $\sim r^{1.1}$ baseline model, though the difference is only weakly significant ($\approx 1.6\sigma$).

In Figure 6, we also show the baseline gravity-only model. The entropy profile of Mrk 1216 lies well above it testifying to the presence of nongravitational heating. Rescaling the entropy profile by ($f_{gas}/f_{b,U}$)$^{2/3}$, where $f_{gas}$ is the cumulative gas fraction and $f_{b,U} = 0.155$ is the cosmic baryon fraction, results in a much better agreement with the gravity-only model, especially within the region covered by the Chandra data. This suggests that the nongravitational heating has not increased the gas temperature, but instead has redistributed the gas spatially. This result is very consistent with those we have obtained previously for the massive isolated elliptical galaxies NGC 720 (Humphrey et al. 2011), NGC 1521 (Humphrey et al. 2012b), and NGC 6482 (B17) and results for galaxy clusters (e.g., Pratt et al. 2010).

We mention that we investigated adding a break radius to the entropy (see Equation (3) of B17) and found the data did not require it. Including such a break yielded an entropy profile and overall HE solution that is very consistent with the no-break case.

6.4.3. DM Profile

While the DM halo is clearly required (Section 6.4.1), the data do not distinguish between profiles with central cusps (NFW, Einasto) and cores (logarithmic potential $\ln(r_c^2 + r^2)$). Moreover, fits using the NFW and Einasto profiles are indistinguishable and yield similar parameter values. These results are fully consistent with what we found for NGC 6482 (B17).

6.4.4. SMBH

While we fixed the SMBH mass by default in our models, we found that the Chandra data were able to constrain $M_{\text{BH}}$, albeit weakly. The key reason why only weak constraints are possible with the present data is because the central aperture has a radius of $1'7$, whereas the SMBH radius of influence is $r_s \approx 0.5'$. Using a flat prior for $M_{\text{BH}}$ over the range $(0.3–20) \times 10^9 M_\odot$, we obtain $M_{\text{BH}} = (5 \pm 4) \times 10^9 M_\odot$, with a 90% upper limit of $M_{\text{BH}} = 1.4 \times 10^{10} M_\odot$, which is very consistent with the recent stellar dynamical measurement by Walsh et al. (2017).

If instead we use a flat prior on the logarithm, the SMBH is not detected and a more stringent upper limit is indicated: $M_{\text{BH}} = (1.4 \pm 1.7) \times 10^9 M_\odot$, with a 99% upper limit of $M_{\text{BH}} = 9.4 \times 10^9 M_\odot$. The sensitivity of $M_{\text{BH}}$ to the prior shows that the parameter is not constrained robustly by our bayesian analysis. A standard frequentist $\chi^2$ fit yields $M_{\text{BH}} = (3.9 \pm 2.6) \times 10^9 M_\odot$ more in line with the result for
the flat (non-logarithm) prior. We conclude that the present data are consistent with the $M_{\text{BH}}$ determination by Walsh et al. (2017), and improvement in the constraint awaits precise measurements of the hot ISM properties in a smaller aperture closer to $r_e$.

We note that omitting the SMBH from the HE models has a negligible impact on the quality of the fit. Consequently, the centrally peaked temperature profile (Figure 5) is not caused by the gravitational influence of the SMBH, nor is it due to hard emission from an AGN (Section 6.2). The centrally peaked temperature profiles observed in several massive elliptical galaxies (e.g., NGC 6482, B17) may be explained by classical wind models (e.g., Ciotti et al. 1991; David et al. 1991).

### 6.4.5. Stellar Mass and IMF

The result we obtain for the stellar mass-to-light ratio, $M_*/L_H = 1.33 \pm 0.21$ solar, agrees very well with the stellar dynamical analysis of Walsh et al. (2017), who found $M_*/L_H = 1.3 \pm 0.4$ solar. Walsh et al. (2017) report their value also agrees with that of Y17 and is consistent with single-burst stellar population synthesis models with either a Kroupa ($M_*/L_H = 1.2$ solar) or a Salpeter ($M_*/L_H = 1.7$ solar) initial mass function (IMF). However, the smaller error bar we obtain for $M_*/L_H$ remains fully consistent with the Kroupa IMF, but is marginally inconsistent ($\approx 2\sigma$) with the Salpeter IMF.

The agreement with a Kroupa (or Chabrier) IMF we find for Mrk 1216 is typical for X-ray HE studies of massive elliptical galaxies (see the discussion in Section 8.3 of B17). We also note that our result for Mrk 1216 is not dependent on our use of the accurate MGE model of the $H$-band light (Section 6.3). If instead we use a de Vaucouleurs model with the half-light radius from the Two Micron All-Sky Survey (2MASS) Extended Source Catalog (Jarrett et al. 2000), we obtain $M_*/L_H = 1.24 \pm 0.19$ solar, which is very consistent with the MGE result.

Finally, we note that the good agreement of the values of $M_*/L_H$ obtained by us and Walsh et al. (2017) supports the accuracy of the mass-measurement techniques used by both studies; i.e., in our case, the accuracy of the hydrostatic equilibrium approximation for Mrk 1216. Note also that the consistency of the stellar mass supports the stellar mass-size relation for CEGs obtained by Y17, indicating that the structure of the CEGs matches the redshift $\sim 2$ red nugget population rather than the low-redshift ETG population.

### 6.4.6. Density Slope and DM Fraction

Y17 report an average total mass density slope $\langle \gamma \rangle = 2.3$ within $r = R_e$ for their sample of 16 CEGs. This modestly exceeds the average slopes of normal massive local ETGs ($2.15 \pm 0.03$, intrinsic scatter 0.10) obtained by Cappellari et al. (2015) that is also within $R_e$. In Table 5, we list mass-weighted slopes evaluated for several radii. We obtain $\langle \gamma \rangle = 2.22 \pm 0.08$ within $r = R_e$, which agrees very well with the average CEG value from Y17 and is also consistent with the local ETGs.

Both the average slope we obtain for Mrk 1216 within $R_e$ and its variation with radius broadly agree with the average results of Y17 for CEGs. The CEGs reported by Y17 have average slopes that decrease with radius from a value of 2.3 within $R_e$ to 1.99 at a larger radius. As seen in Table 5, $\langle \gamma \rangle$ for Mrk 1216 decreases with an increasing radius out to $10 R_e$, and (not shown) begins to increase soon after. For a comparison, the instantaneous slope (i.e., not mass-weighted) is $\approx 2.3$ near the center, reaches a minimum value of $\approx 1.7$ at $r \approx 3 R_e$, and increases for larger radii approaching the slope of 3 for the NFW profile. Cappellari et al. (2015) find an average slope of $2.19 \pm 0.03$ with 0.11 scatter over 0.1 $R_e$ to $4 R_e$ for normal ETGs, which is significantly larger than the mass-weighted slope we measure within $4 R_e$ (1.90 \pm 0.07). Hence, like the CEGs studied by Y17, for Mrk 1216 we obtain smaller density slopes than the normal ETGs for radii larger than $R_e$ out to $4 R_e$. (We note that the slope of NGC 6482 (B17) is consistent with the normal ETGs.)
Turning to the DM fraction, Y17 obtained $f_{DM} = 0.11$ within $r = R_e$ for the CEGs, which is lower than the value 0.19 of the normal ETGs studied by Cappellari et al. (2015) and accounts for the higher mass range of the CEGs (see Y17). We obtain $f_{DM} = 0.20 \pm 0.07$ (Table 5) for Mrk 1216, which agrees very well with the normal ETGs and is nearly double the value of the CEGs, though the difference is only weakly significant.

Finally, the slope–$R_e$ relation (Humphrey & Buote 2010; see also Auger et al. 2010),

$$\gamma = 2.31 - 0.54 \log(R_e/\text{kpc}),$$

predicts an average slope 2.11 for Mrk 1216 over 0.2–10 $R_e$. The mass-weighted slope we obtain (Table 5) is $\approx 11\%$ below the predicted value, but is within the observed scatter (Auger et al. 2010); note B17 found NGC 6482 had a slope $\approx 12\%$ above the predicted value.

6.4.7. Halo Concentration and Mass

Whereas Y17 and Walsh et al. (2017) were unable to constrain the DM halo concentration using stellar dynamics, we obtain interesting constraints ($c_{200} = 17.5 \pm 6.7$ and $M_{200} = (9.6 \pm 3.7) \times 10^{12} M_\odot$; Table 4), despite the short Chandra exposure. These best-fitting values exceed the value $c_{200} = 6.6$ of the mean $c_{200}$–$M_{200}$ relation from LCDM by $\approx 4\sigma$ (Dutton & Macciò 2014). While the discrepancy is only $\approx 2\sigma$ significant in terms of the measurement error, the large $c_{200}$ may provide evidence for weak adiabatic contraction as we argued for NGC 6482; i.e., the “forced quenching” model of Dutton et al. (2015) implemented as the AC4 model in B17 yields a similar $M_{200}$ and a smaller $c_{200} = 15$ that are less discrepant ($\approx 3\sigma$) with the mean LCDM relation (and does not alter the best-fitting $M_e/L_H$).

In fact, the concentration discrepancy may be even larger for Mrk 1216. Unlike the results quoted previously for other model parameters (e.g., $M_e/L_H$), we find that the concentration values differ by $>1\sigma$ error depending on how we define the Bayesian best-fitting value. Above we have focused on the Best Fit values (see Section 6.4.1). For well-constrained parameters, the Best Fit and Max Like parameter values closely correspond; e.g., see the results for NGC 6482 (B17) and RXJ 1159+5531 (Buote et al. 2016). But the concentration and virial mass, which are global halo parameters, are not very well constrained for Mrk 1216 since the Chandra measurements of the gas temperature and density currently extend only out to an average binned radius $\approx R_{200}/3$.

The Max Like values we obtain, $c_{200} = 25.9$ and $M_{200} = 5.1 \times 10^{12} M_\odot$ where $c_{200}$ is over $5\sigma$ above the mean LCDM relation, are almost as discrepant as NGC 6482 (B17). We note also that the Max Like parameters closely correspond to those obtained from a standard frequentist $\chi^2$ fit, i.e., $c_{200} = 25.5$ and $M_{200} = 5.4 \times 10^{12} M_\odot$.

6.4.8. Gas and Baryon Fraction

Results qualitatively similar to the concentration are obtained for the global baryon fraction ($f_{b,200}$). While the mean Best Fit value ($f_b,200 = 0.070 \pm 0.045$) is less than half (and $\approx 2\sigma$ below) the cosmic value (0.155), the Max Like value (0.14) is fully consistent with it. Which of these two values of the baryon fraction better approximates reality is important when considering the “Missing Baryons Problem” at low redshift (Fukugita et al. 1998). If the higher value prevails, it would lend support to the notion that, at least in massive elliptical galaxy/small group halos, most of the baryons could be located in the outer halo as part of the hot component—which would be consistent with our results obtained previously.
Best values and error estimates (see Section 6.4.1) for the fundamental free parameters of the fiducial HE model. $P_{\text{ret}}$ refers to the total gas pressure evaluated at the reference radius $r = 10$ kpc and serves as the boundary condition for the hydrostatic model. The parameters $s_0$, $s_1$, and $\alpha$ specify the power law plus constant entropy profile. The fundamental mass parameters are the $H$-band stellar mass-to-light ratio ($M_*/L_H$), and the concentration and enclosed total mass ($M_{\text{enc}}$) computed within $r_{200}\text{.}$ Note the gas and baryon fraction parameters are derived from the mass model.

### Table 4

| $P_{\text{ret}}$ $(10^{-2}$ keV cm$^{-3}$) | $s_0$ (keV cm$^2$) | $s_1$ (keV cm$^3$) | $\alpha$ | $M_*/L_H$ ($M_*/L_H^{-1}$) | $c_{200}$ | $M_{\text{enc}}$ $(10^{12} M_\odot)$ | $f_{\text{gas,200}}$ | $f_{\text{b,200}}$ |
|---|---|---|---|---|---|---|---|---|
| Best Fit | 0.98 $\pm$ 0.10 | 2.49 $\pm$ 1.19 | 2.07 $\pm$ 0.71 | 0.92 $\pm$ 0.11 | 1.33 $\pm$ 0.21 | 17.5 $\pm$ 6.7 | 9.6 $\pm$ 3.7 | 0.05 $\pm$ 0.039 | 0.070 $\pm$ 0.045 |
| (Max. Like) | (0.95) | (1.31) | (2.40) | (0.86) | (1.36) | (25.9) | (5.1) | (0.106) | (0.137) |

Note. Best fit and error estimates for the fiducial HE model. $P_{\text{ret}}$ refers to the total gas pressure evaluated at the reference radius $r = 10$ kpc and serves as the boundary condition for the hydrostatic model. The parameters $s_0$, $s_1$, and $\alpha$ specify the power law plus constant entropy profile. The fundamental mass parameters are the $H$-band stellar mass-to-light ratio ($M_*/L_H$), and the concentration and enclosed total mass ($M_{\text{enc}}$) computed within $r_{200}\text{.}$ Note the gas and baryon fraction parameters are derived from the mass model.

### Table 5

| Radius (kpc) | $f_{\text{DM}}$ |
|---|---|
| 2.3 | 1.0 | 2.22 $\pm$ 0.08 | 0.20 $\pm$ 0.07 |
| 4.6 | 2.0 | 2.07 $\pm$ 0.09 | 0.38 $\pm$ 0.09 |
| 9.2 | 4.0 | 1.90 $\pm$ 0.07 | 0.60 $\pm$ 0.07 |
| 23.0 | 10.0 | 1.87 $\pm$ 0.13 | 0.82 $\pm$ 0.03 |

Note. The mass-weighted slope is evaluated for the fiducial HE model using Equation (2) of Dutton & Treu (2014). The DM fraction is defined at each radius $r$ as $f_{\text{DM}} = M_{\text{DM}}(r)/M_{\text{tot}}(r)$.

We have considered an extensive number of systematic tests and examined their impact on the measured parameters of the HE model. Some of these have been discussed in previous sections; e.g., adding a break radius to the entropy profile (Section 6.4.2), using a de Vaucouleurs profile of the stellar light (Section 6.4.5). We considered most of the systematic tests discussed in Section 7 of B17. However, due to the relatively large statistical errors on the HE parameters for Mrk 1216, we find all of those systematic errors to be negligible in that they are less than the 1σ statistical errors. Consequently, in this section, we only summarize a few notable tests associated with choices in the spectral analysis (Sections 4 and 6.2) and the treatment of the plasma emissivity in the HE models (Section 6.3). All of these tests had no significant effect on the HE parameters.

**Constant Metallicity.** Whereas the results we have presented allow the metallicity to vary with radius, we also considered the constant metallicity solution reported in Section 6.2.

**Soft CXB.** We examined adjusting the fluxes of the soft CXB components by factors of 0.5 and 2.

**Unresolved LMXBs.** We examined adjusting the nominal flux of the unresolved LMXB component by factors of 0.5 and 2.

**Plasma Emissivity.** The plasma emissivity $\Lambda_e(T, Z)$ in our fiducial HE model is evaluated self-consistently at any radius using the temperature of the model. The metallicity used to evaluate $\Lambda_e(T, Z)$ at any radius is obtained by fitting a projected, emission-weighted smooth model to the measured metallicity profile (Table 3). The smooth model we use is essentially a $\beta$ model plus a constant. For a comparison, we also adopted the procedure we have favored in our previous studies (e.g., see Section 4 of B17) of interpolating the radial grid established by the measured binned metallicities in projection as a proxy for the 3D metallicity profile.

### 7. Discussion and Conclusions

We have found for Mrk 1216 that the entropy profile and global mass properties ($c_{200}$, $M_{\text{enc}}$) are very similar to those of the fossil group NGC 6482 (B17) and the massive, isolated nearly fossil systems NGC 720 (Humphrey et al. 2011) and NGC 1521 (Humphrey et al. 2012b). Although, for PGC 032873, the *Chandra* data did not allow for a detailed HE analysis, we can place its X-ray properties in context, along with those of Mrk 1216, through a comparison with global X-ray scaling relations.

The ETG scaling relations for local galaxies seriously underpredict the X-ray luminosities we have measured for Mrk 1216 and PGC 032873. The $L_x$–$T_x$ relation reported by Goulding et al. (2016) for the most massive nearby ellipticals predicts $L_x \approx 7 \times 10^{40}$ erg $s^{-1}$ in the 0.3–5.0 keV band for Mrk 1216, while we measure a value of $\sim 1 \times 10^{42}$ erg $s^{-1}$ in the same band that is a factor of $\sim 14$ times larger. For PGC 032873, the difference is a factor of $\sim 3$. The $L_x$, $L_{K_s}$, $\sigma_x$ scaling relation of Goulding et al. (2016) yields even larger factors. The fact that Mrk 1216 and PGC 032873 have $L_x$ values that greatly exceed the scaling relations of normal ETGs is unsurprising since the total masses inferred for these galaxies ($\sim 10^{13} M_\odot$) indicate group-scale halos (even though both galaxies are rather isolated—e.g., Ferré-Mateu et al. 2017). Indeed, using the $L_x$–$T_x$ results for galaxy groups by Loovisari et al. (2015) with the average temperatures we have measured (Table 1) yields a good agreement for Mrk 1216, but overpredicts $L_x$ for PGC 032873 by a factor of $\sim 5$; i.e., PGC 032873 lies roughly midway between the scaling relations for ETGs and groups.

If these CEGs are indeed largely untouched descendants from the $z \sim 2$ population of red nuggets (Ferré-Mateu et al. 2017; Y17) that undergo little “phase 2” stellar accretion

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4. Although NGC 720 and NGC 1521 are typically classified as members of larger groups owing to more distant galaxy associations, we refer to them as “nearly” fossil systems since they obey the fossil classification within their projected virial radii.

5. In these comparisons, we have used the “full aperture” scaling relations of Goulding et al. (2016) defined within the radius where the diffuse hot gas flux equals the background. For Mrk 1216, this corresponds to Annulus 7 and leads to an $L_x \approx 0.95\%$ of the value at 100 kpc listed in Table 1. For PGC 032873, the corresponding radius is $\approx 0.3$ and $L_x \approx 0.6$ of the value at 100 kpc.
over that time, it is remarkable that they are each the dominant central galaxy in a group-size halo. Apparently all the merging in these groups occurred in the assembly of the red nugget, making these systems truly ancient fossil groups.

The results we have presented in this paper were first summarized in observing proposals submitted to the Chandra AO19 and XMM-Newton AO17 calls for proposals in 2017. Both proposals were approved for deep follow-up observations of Mrk 1216.

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