Thermodynamic properties, multiphase gas, and AGN feedback in a large sample of giant ellipticals

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ABSTRACT
We present a study of the thermal structure of the hot X-ray emitting atmospheres for a sample of 49 nearby X-ray and optically bright elliptical galaxies using Chandra X-ray data. We focus on the connection between the properties of the hot X-ray emitting gas and the cooler H $\alpha$+[N II] emitting phase, and the possible role of the latter in the Active Galactic Nuclei (AGN) feedback cycle. We do not find evident correlations between the H $\alpha$+[N II] emission and global properties such as X-ray luminosity, mass of hot gas, and gas mass fraction. We find that the presence of H $\alpha$+[N II] emission is more likely in systems with higher densities, lower entropies, shorter cooling times, shallower entropy profiles, lower values of min(t_{cool}/t_{ff}), and disturbed X-ray morphologies (linked to turbulent motions). However, we see no clear separations in the observables obtained for galaxies with and without optical emission line nebulae. The AGN jet powers of the galaxies with X-ray cavities show hint of a possible weak positive correlation with their H $\alpha$+[N II] luminosities. This correlation and the observed trends in the thermodynamic properties may result from chaotic cold accretion (CCA) powering AGN jets, as seen in some high-resolution hydrodynamic simulations.

Key words: galaxies: active – galaxies: evolution – galaxies: formation – X-rays: galaxies.

1 INTRODUCTION
Until the 1980s, elliptical galaxies were thought to be gasless dormant systems containing mostly old stars, a picture that was drastically changed with the advent of sensitive instruments in the X-ray, infrared, and mm-bands. Many elliptical galaxies are now known to host a complex multiphase interstellar medium, ranging from the cold $\lesssim$30 K molecular clouds traced by sub-mm CO lines (Edge 2001; Edge & Frayer 2003; Salomé & Combes 2003; McDonald, Wei & Veilleux 2012; Temi et al. 2018); the cool $\sim$100 K gas detected through the FIR cooling lines of [C II], [N II], and [O I] (Edge et al. 2010; Mittal et al. 2011, 2012; Werner et al. 2013); the warm $\sim$1000 K H$_2$ molecular gas seen in the NIR (Jaffe & Bremer 1997; Falcke et al. 1998; Donahue et al. 2000; Edge et al. 2002; Hatch et al. 2005; Jaffe, Bremer & Baker 2005; Johnstone et al. 2007; Oonk et al. 2010; Lim et al. 2012); the ionized $\sim$10 000 K nebulae seen in the optical H $\alpha$+[N II] emission (Cowie et al. 1983; Johnstone, Fabian & Nulsen 1987; Heckman et al. 1989; Donahue, Stocke & Gioia 1992; Crawford et al. 1999; McDonald et al. 2010); the moderately hot $\sim$100 000 K gas detected in the FUV (Sparks et al. 2012); and the very hot $\sim$10$^7$ K X-ray gas.

The role of the cool gas in feeding the active galactic nuclei (AGN) in these systems has remained an open question. The correlation between the jet powers, calculated from the radio-filled X-ray cavities, and the Bondi accretion rate of hot gas found by Allen et al. (2006) initially suggested ongoing hot accretion in giant ellipticals although Russell et al. (2013) later on did not find a clear correlation in a larger sample.
Using high-resolution 3D hydrodynamic simulations of massive galaxies, Gaspari, Ruszkowski & Oh (2013), Gaspari, Brighenti & Temi (2015), and Gaspari et al. (2018) found that ‘chaotic cold (gas) accretion’ (CCA) plays an important role in the evolution of the central supermassive black hole (SMBBH) and the host galaxy; this view has also been supported in other similar studies (Prasad, Sharma & Babul 2015). However, the exact nature of the material feeding and powering the AGN is still a subject of debate.

The cool gas in giant ellipticals has most likely an internal origin and formed through the radiative cooling of the hot X-ray emitting gas and through stellar mass-loss. Werner et al. (2014) analysed a sample of 10 optically and X-ray bright giant ellipticals, and found that the galaxies with extended cool gas nebulae have significantly lower entropies than the galaxies without cool gas, with a clear separation in the entropy profiles of the two groups. This indicates that the cool gas resulted from the radiative cooling of the hot phase. The cool gas develops through the formation of cooling instabilities from the hot gas, and feeds the central AGN; the radio-mode feedback from the central AGN then heats the surrounding hot medium preventing it from cooling catastrophically, thus completing what is known as the ‘AGN feedback cycle’ (see Fabian 2012; McNamara & Nulsen 2012; Soker 2016, for reviews).

This scenario would lead to a correlation between the properties of the hot and cool phases. The ratio $t_{\text{cool}}/t_{\text{ff}}$, where $t_{\text{cool}}$ is the local cooling time and $t_{\text{ff}}$ is the free-fall time of a cooling blob, was found to be an important parameter for the formation of cooling instabilities (see Gaspari, Ruszkowski & Sharma 2012b; McCourt et al. 2012; Sharma et al. 2012). Based on hydrodynamic simulations of massive ellipticals and clusters of galaxies, it has been found that $t_{\text{cool}}/t_{\text{ff}} \lesssim 10$ is the critical condition for the cooling instabilities to form in the cores of these systems. This result was also found to be supported observationally (see Cavagnolo et al. 2009; Lakhchaura, Saini & Sharma 2016), although recently there have been some disagreements on the robustness of the cooling instability threshold (Hogan et al. 2017; Pulido et al. 2018; Babyk et al. 2018a).

McNamara et al. (2016) and Voit et al. (2017) found that the formation of cooling instabilities is also promoted by the adiabatic uplift of the hot gas by rising AGN jet-inflated bubbles. Based on results obtained from both hydrodynamic simulations and observations, Gaspari et al. (2018) found that condensations are also promoted by subsonic turbulence and suggested the criterion $t_{\text{cool}}/t_{\text{eddy}} \approx 1$, where $t_{\text{eddy}}$ is the turbulent eddy time, to be the best tracer of multiphase gas. Thus, in addition to entropy profiles and the $t_{\text{cool}}/t_{\text{ff}}$ ratio, gas motions should also be investigated in order to understand the formation of cooling instabilities in massive haloes.

An alternative explanation for the presence/absence of multiphase gas in giant elliptical galaxies was given by Voit et al. (2015). Based on the results obtained for the small sample of Werner et al. (2014), Voit et al. (2015) found that all but one (NGC 4261) of the five single-phase galaxies in the sample were found to have $t_{\text{cool}}/t_{\text{ff}} \geq 20$ while all five multiphase galaxies had $5 < t_{\text{cool}}/t_{\text{ff}} \lesssim 20$, in the 1–10 kpc radial range. They suggest that the single-phase and multiphase ellipticals are two intrinsically different categories of massive ellipticals. While in the single-phase ellipticals, the feedback from supernova explosions prevents the stellar ejecta from forming stars by sweeping it out of the galaxy, in multiphase ellipticals, supernova feedback is not sufficient and the central AGN feedback maintains $t_{\text{cool}}/t_{\text{ff}} \approx 10$. Although the study was based on a small sample of galaxies, similar results were also obtained in the hydrodynamic simulations of Wang, Li & Ruszkowski (2018).

So far, most of the studies related to the non-gravitational processes (gas cooling/heating and AGN feedback) have focused on bright massive clusters of galaxies. However, to understand the details of these processes better, it is crucial to also study the giant elliptical galaxies, where we can resolve the central regions (where most of the non-gravitational processes take place) in a greater detail than in clusters.

In this work, we have analysed the X-ray and Hα+[N II] observations of a sample of 49 nearby X-ray and optically bright elliptical galaxies, in order to understand the cool–hot gas connection, their interplay and their role in the AGN feedback cycle. About 19 of the 49 galaxies are the central galaxies of their respective groups; four are central galaxies of clusters; 23 are non-central galaxies of groups/clusters and three are isolated/fossil galaxies. Our sample has a high degree of completeness above certain X-ray and optical luminosity thresholds (see Section 2.1). The sample selection is described in Section 2.1, and the data reduction and analysis are detailed in Section 2.2. The results are presented in Section 3, discussed in Section 4, and the conclusions are summarized in Section 5. A lambda cold dark matter cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_M = 0.3$ ($\Omega_\Lambda = 0.7$) has been assumed throughout.

2 SAMPLE AND DATA

2.1 Sample selection

We started with the parent sample of Dunn et al. (2010) and selected 52 galaxies within 100 Mpc for which archival Chandra X-ray observations were available. We also included an additional 16 X-ray and optically bright galaxies which were missing from the original selection (e.g. NGC 5813). To make our sample represent the actual population of nearby bright ellipticals, we selected our final sample based on the intrinsic properties of the galaxies (the X-ray luminosity of the hot gas and the absolute visible band magnitude).

The $0.5–7.0$ keV X-ray luminosities at $r < 10$ kpc for all the galaxies (see Section 2.2 and Section 3.1) are given in Table 1. We obtained the visible band magnitudes for the entire sample from the NASA/IPAC Extragalactic Data Base (NED, Mazzarella et al. 2001), which were then converted to absolute magnitudes ($M_B$) based on the mean redshift-independent distances given in NED (see Table 1). We applied a lower limit of $10^{40}$ erg s$^{-1}$ to the $0.5–7.0$ keV X-ray halo luminosity and an upper limit of $-20$ to $B_B$. These selection criteria led to a sample size of 54. Due to short exposure times, the Chandra observations of four of the 54 systems provided too few counts for the temperature within 10 kpc to be determined with a sufficient accuracy, rendering them unsuitable for detailed analysis. Also, the X-ray emission from the galaxy IC310 was found to be strongly dominated by the central point source. After excluding these five systems, our final sample was reduced to 49 galaxies.

For the $H\alpha+[N\ II]$ information presented in this work, we have mainly used the results from an analysis of the $H\alpha+[N\ II]$ observations carried out using the SOAR optical Imager (SOI) and Goodman High Throughput Spectrograph of the 4.1 m SOuthern Astrophysical Research (SOAR) telescope (Connor et al., in preparation), as well as the Apache Point Observatory (APO) Astrophysics Research Consortium (ARC) 3.5 m telescope (Sun et al., in preparation). Note that, the $H\alpha+[N\ II]$ morphology information presented in this paper comes from the APO and SOAR data, while the luminosities are taken from the literature.

Significant $H\alpha+[N\ II]$ emission was detected in about half (24/49) of the galaxies. Based on the SOAR/APO results, we classified the $H\alpha+[N\ II]$ morphologies of our sample into four categories. These include no cool gas emission (N; total 20 galaxies), nuclear emission (NE; 12 galaxies with $H\alpha+[N\ II]$ emission extent $< 2$ kpc),
extended filamentary emission (E: 13 galaxies with H α+[N II] emission extent ≥ 2 kpc), and unsure (U: four galaxies for which presence/absence of H α+[N II] emission could not be confirmed). The 10th and 11th columns of Table 1 show the morphology class (based on the SOAR/APO results) Connor et al., in preparation; Sun et al., in preparation) and the luminosities (from literature) of the H α+[N II] emission for the sample. The detailed discussion on the imaging and spectroscopic data from SOAR and APO will be presented in two papers (Connor et al., in preparation; Sun et al., in preparation). The depth of the SOAR data is comparable with the APO data, both for imaging and spectroscopy. Both telescopes have similar mirror sizes and similar optical instruments for imaging/spectroscopy. Within 9 arcmin diameter of the nucleus, the 5σ limit reached by our data is 5 × 10⁻¹⁵ erg s⁻¹ cm⁻² – 2 × 10⁻¹⁴ erg s⁻¹ cm⁻², depending on the continuum brightness. Since the limit is essentially an equivalent width limit, our final constraint on the emission-line luminosity is better than 5 × 10⁻¹⁹ erg s⁻¹ (see Werner et al. 2014, for comparison). Some of the H α+[N II] flux estimates in Table 1, are taken from Macchetto et al. (1996) and are based on narrow band H α+[N II] images. In these observations, the stellar continuum is removed by subtracting a scaled broad R-band image from the narrow band H α+[N II] image. The scaling factor is a critical parameter in such an analysis, and various factors (e.g. a non-uniform colour
across the field) may lead to wrong stellar continuum subtraction leading to spurious detections, especially when the \( \text{H} \alpha + [\text{N} \text{II}] \) emission is uniform (non-detected). As an example, for the galaxies NGC 1399 and NGC 4472, Macchetto et al. (1996) detected significant emission with disc-like morphologies, although no significant \( \text{H} \alpha + [\text{N} \text{II}] \) emission was detected in the SOAR images and spectra. Therefore, we caution our readers that some of the disc-like emission detected in Macchetto et al. (1996) might be an artefact, and hence the accuracy of the flux estimates is limited by that of the stellar subtraction.

2.2 X-ray data reduction and analysis

2.2.1 Data reduction

We obtained the publicly available Chandra observations for our sample from the High Energy Astrophysics Science Archive Research Centre (HEASARC). The observation log for all the data used in the analysis is given in Table A1. We used CIAO version 4.9 (Fruscione et al. 2006) and CALDB version 4.7.3 for the data reduction, and the X-ray spectral fitting package XSPEC version 12.9.1 (Arnaud 1996) for the spectral analyses. Throughout the paper, the metallicities are given with respect to the Solar abundances of Grevesse & Sauval (1998). All the data were reprocessed using the standard chandra_repro tool. Periods of strong background flares were filtered using the lc_clean script, and the threshold was set to match the blanksky background maps. Point sources were detected using the CIAO task wavdetect with a false-positive probability threshold of \( 10^{-6} \), they were verified by visual inspection of the X-ray images and finally filtered (except for the central point sources, see Section 2.2.2) from the event files. Note that, the point source detection is prone to be affected by the quality of data and signal-to-noise ratio, especially for faint sources.

2.2.2 Central X-ray point sources

For the galaxies for which central point sources (coinciding with the galaxy’s X-ray emission peak) were detected, a visual inspection was not sufficient for verification. For these central sources, X-ray spectra were extracted from the central regions of radius 3 pixels (1.476 arcsec). The spectra were first modelled with a wabs*apec model and then with a wabs(apec+pow) model in XSPEC; the power-law index was frozen to 1.5.\(^1\) For some of the sources an additional absorption zwabs model was required with the power law to account for the intrinsic absorption of the AGN. The sources were confirmed if the addition of the power-law component lead to a significant improvement in the fit. In the end, central point sources were confirmed in 16 of the 49 galaxies of our sample. Interestingly, 11 of the 16 galaxies were found in systems containing cool gas (NE and E) while only three were in systems with no detectable optical emission line nebulae (N); the remaining two galaxies were in the unsure (U) systems. Note however that based on the radio flux densities given in the literature (Dunn et al. 2010; Brown et al. 2011), practically all galaxies in our sample harbour central radio sources (except NGC 2305 for which we did not find a reported detection).

\(^1\)To avoid the degeneracy between the apec and pow components, it was required to freeze the power-law index. The value of 1.5 is consistent with the values typically seen for such sources (David et al. 2009).

The intrinsic 2–10 keV central AGN luminosities estimated from the power-law components of the spectral models and their ratio with the Eddington luminosities are given in the eighth and ninth columns of Table 1, respectively. The Eddington luminosities were calculated using the relation \( L_{\text{edd}} = 1.26 \times 10^{47} (M_{\text{BH}}/10^5 M_\odot) \) erg s\(^{-1}\) (Russell et al. 2013). The Black Hole masses \( (M_{\text{BH}}) \) were estimated from the empirical correlation of \( M_{\text{BH}} - \sigma_\star \) relation (Gebhardt et al. 2000; Tremaine et al. 2002), \( M_{\text{BH}} = 10^{8.13} (\sigma_\star/200 \text{ km s}^{-1})^{4.02} M_\odot \). The velocity dispersions \( (\sigma_\star) \) were obtained from the Hyperleda data base (Makarov et al. 2014). For NGC 4486 (M87), the central source was heavily affected by pile-up, therefore the AGN luminosity of González-Martín et al. (2009) was used. All the AGNs are found to have very low Eddington ratios (<10\(^{-5}\)) and seem to be operating in the gentle radio mechanical feedback mode. For the remaining analyses, the central point sources for all the 16 galaxies were removed by excluding the central regions of radius 3 pixels (1.476 arcmin).

2.2.3 Spectral extraction

For this study, we determined emission-weighted average properties within a radius of 10 kpc as well as the deprojected radial profiles of the thermodynamic properties of the hot diffuse haloes. For the average properties, we restricted the spectral analyses to \( r < 10 \text{ kpc} \) for most of the galaxies, see Goulding et al. (2016) since the hot gas properties within this region are dominated by the galaxy scale physics. For this, spectra were extracted from a circular region within \( r < 10 \text{ kpc} \) centred on the galaxy’s X-ray peak, using the CIAO task specextract. For the radial profiles, spectra were extracted from a number of circular annuli centred on the X-ray peak. The radial ranges of the annuli were chosen based on the requirement that each annulus should have at least 100 counts in the 0.5–5 keV energy range. The total number of annuli was limited to be \( <25 \). For the radial analyses, the spectra from the outermost annuli in some of the galaxies may be contaminated by the emission from the surrounding group or cluster. However, the values obtained for these annuli do not affect our main results.

2.2.4 Background spectra

For each source spectrum, corresponding background spectra were extracted from the standard Chandra blanksky background event files matching the source observations, obtained from Maxim Markovitch’s blanksky background data base. The event files were reprojected to match the source observations. To match the time-dependent particle background levels in the source and blanksky observations, all the blanksky spectra were scaled by the ratio of the 9.5–12 keV count rates of the source and blanksky observations. We also checked for contamination by soft Galactic foreground (most significant in the outermost annuli) and for differences in the Galactic foreground level in the scaled blanksky and source spectra. For this, we obtained the ROSAT All Sky Survey 0.47–1.21 keV (RASS 45 band) count rates from the outer 0.7–1.0 degree annular regions around each galaxy using the HEASOFT X-ray background tool. These count rates were compared with the source count rates in the outermost annuli. For most of our galaxies (39/49), the R45 count rates were \(< 10 \% \) of the total 0.47–1.21 keV count rates.

We chose the two worst affected sources, NGC 4552 and NGC 4778 (HCG 62), for which the RASS R45 count rate was
2.2.5 Spectral analysis

The spectra for the central $r = 10$ kpc were fitted with a single-temperature absorbed APEC model in XSPEC, using the C-statistics. A thermal bremsstrahlung component with $kT = 7.3$ keV was added to account for the unresolved point sources (see Irwin, Athey & Bregman 2003). The neutral hydrogen column density was obtained from the Swift Galactic $N_H$ tool which gives the total (atomic+molecular) X-ray absorbing hydrogen column density, using the method of Willingale et al. (2013). The redshift was fixed to the value obtained from the SIMBAD data base (Wenger et al. 2000). The abundances of Mg, Si, and Fe were kept free for this analysis. However, for the galaxies for which the abundances could not be constrained, they were frozen to one-third of the solar value, which is the value obtained for most of the galaxies in the sample.

For the radial profiles, all the metallicities were frozen to the values obtained from the above analysis of the central 10 kpc radius regions. For low-temperature systems ($kT \sim 0.5$–1.0 keV), this assumption might lead to an underestimation of metallicities and overestimation of densities (see Buote 2000; Werner et al. 2008), particularly in the inner regions where the gas is expected to be multiphase. However, for many of the galaxies, the data quality did not allow us to resolve the multitemperature structure and the metallicities could not be constrained for the individual annuli. Therefore, to analyse the entire sample in a uniform way, we assumed the central 10 kpc region metallicities when fitting the radial profiles. Note that underestimating the metallicity by a factor of 2, will result in overestimating the density by a factor of $\sim 1.35^2$ (Werner, Allen & Simionescu 2012).

The deprojection analysis to determine the radial profiles of thermodynamic quantities was performed using the project model in XSPEC. The free parameters in the fit were the temperature and normalization of the APEC component and the normalization of the bremsstrahlung component (not deprojected). We assumed a constant density and temperature in each 3D shell. The APEC normalizations ($\eta$) were converted to the individual shell gas densities ($n = n_e + n_p$) using the relation

$$\eta = 10^{-14} \int n_e n_p dV \frac{4\pi D_A^2(1+z)^2}{n \epsilon_{\text{cool}}}.$$  

(1)

We also checked for the effect of using projected metallicity profiles (with 2T apec models for the inner shells) instead of fixed metallicities, for two (a cool gas free and a cool gas rich) galaxies with high data quality. This lead to very similar changes ($<10$ per cent in the densities, $<20$ per cent increase in the entropy, and $\sim 8$ per cent decrease in the slopes of the entropy profiles) in both the galaxies. We think that for all our galaxies, a free metallicity will shift all the density profiles slightly upwards and the entropy and cooling times profiles downwards, however, the general trends in Figs 2 and 3 will remain the same.

Here $D_A$ is the angular diameter distance to the source, $n_e$ and $n_p$ are the electron and proton number densities, where for a fully ionized gas with one-third solar metallicity $n_e = 0.53n_p$ and $n_p = n_e/1.2$. The densities and temperatures were used to calculate the gas entropy ($K_T = kT n_e^{2/3}$), pressure ($P = nkT$), and cooling time ($t_{\text{cool}} = 1.5nkT(\epsilon_{\text{cool}} A(T, Z))$, where $A(T, Z)$ is the cooling function and $Z$ is the metallicity; note that we are using here the metallicities obtained from the central 10 kpc region spectral analysis).

3 RESULTS

3.1 X-ray properties within $r = 10$ kpc

The spectra for all the 49 galaxies extracted from circular regions of $r = 10$ kpc around the X-ray peaks were analysed as described in Section 2.2. The resulting best-fitting values of the gas temperatures span a range of values from 0.47 keV to 1.64 keV. The 0.5–7.0 keV X-ray luminosities ($L_X$) determined within $r = 10$ kpc span two orders of magnitude from $2.3 \times 10^{40}$ erg s$^{-1}$ to $2.5 \times 10^{42}$ erg s$^{-1}$. The temperatures and X-ray halo luminosities obtained for the entire sample are listed in Table 1. The X-ray halo luminosities plotted versus the average X-ray temperatures of the galaxies are shown in the top left-hand panel of Fig. 1.

3.2 Deprojected profiles

The deprojected temperature ($kT$), density ($n$), entropy ($K$), pressure ($P$), and cooling time ($t_{\text{cool}}$) profiles of the individual galaxies are given in the appendix (Figs A1, A2, A3, A4, and A5, respectively). The $kT$, $n$, $K$, and cooling time ($t_{\text{cool}}$) profiles of the full sample, classified based on the cool gas extents (see Section 2.1) are shown in Fig. 2. The temperature profiles in the top left-hand panel do not show any distinction between the different cool gas morphology/extent groups. The density profiles show higher densities for the extended cool gas (blue) galaxies than the rest of the galaxies. However, at least three (NGC 4936, NGC 6868, and IC 4296) of the 13 extended cool gas galaxies seem to have low densities. Note that, NGC 6868 was found to have indications for a rotating cold gas disc in the velocity distribution maps of [C II] emission (see Werner et al. 2014). It is possible that the cool gas in the low-density galaxies is supported by rotation. In general, the profiles of entropy and cooling time show lower values for the extended cool gas galaxies than the cool gas free galaxies. The three outliers with low density and extended cool gas, also have higher entropies and cooling times than the rest of the extended cool gas galaxies.

To see the trends in the thermodynamic profiles and their scatter more clearly, in Fig. 3 we show the median temperature, density, entropy, and cooling time profiles of the cool gas free (red), nuclear cool gas (green), and extended cool gas (blue) groups. The profiles were obtained by finding the median values in 15 radial bins. The shaded regions show the median absolute deviations (MAD) about the medians for each group. The trends seen in Fig. 2 are much more clearly visible in Fig. 3. The median temperature profiles of the three groups are found to be very similar. The density profiles show higher values for the extended cool gas galaxies than the cool gas free galaxies. In the entropy and cooling time profiles also, the extended cool gas galaxies seem to have lower values than the cool gas free galaxies, especially outside the innermost regions ($\sim 2$ kpc), but with significant spread. The nuclear cool gas galaxies are found to have densities, entropies, and cooling times in between the extended cool gas and cool gas free galaxies.
4 DISCUSSION

4.1 Cooling instabilities and the thermodynamic properties of galactic atmospheres

4.1.1 Correlation with average X-ray properties

The distributions of X-ray luminosities ($L_X$), gas masses ($M_{\text{gas}}$), gas mass fractions ($f_{\text{gas}}$), and the $Y_X = M_{\text{gas}}T_X$ values, within $r < 10$ kpc plotted versus the average X-ray temperatures within the same region (obtained in Section 3.1), for the galaxies without and with different extents of cool gas are shown in Fig. 1. We obtained the gas mass estimates ($M_{\text{gas}}$) and the gas mass fractions ($f_{\text{gas}}$) for all the galaxies within the same 10 kpc radius circular regions. The gas masses were obtained by integrating the densities obtained in Section 3.2 ($M_{\text{gas}}(r) = \int 4\pi r^2 \mu m_{\text{H}} n \, dr$), and the gas mass fractions were obtained as $f_{\text{gas}}(r) = M_{\text{gas}}(r)/M_{\text{tot}}(r)$. The total masses of the galaxies, $M_{\text{tot}}(r)$ within a radius $r$, were obtained from the gas pressure gradients assuming hydrostatic equilibrium. The pressure gradients were determined using smooth empirical fits to the pressure profiles obtained in Section 3.2. We do not see any trends in $L_X$, $M_{\text{gas}}$, and $f_{\text{gas}}$ with the presence or morphology/extent of cool gas.

The linear correlation coefficients in log-space between $L_X-T_X$, $M_{\text{gas}}-T_X$, $f_{\text{gas}}-T_X$, and $Y_X-T_X$ were found to be $0.67 \pm 0.09$, $0.63 \pm 0.10$, $0.48 \pm 0.13$, and $0.75 \pm 0.07$ (obtained using the python $\text{linmix}$ package), and the best-fitting relations were found to be $L_X \propto T_X^{3.1 \pm 0.5}$, $M_{\text{gas}} \propto T_X^{2.6 \pm 0.5}$, $f_{\text{gas}} \propto T_X^{3.6 \pm 0.5}$, and $Y_X \propto T_X^{3.6 \pm 0.5}$, respectively. Our best-fitting $L_X-T_X$ relation is shallower than that found in the group-cluster combined studies (see Kim & Fabbiano 2015; Goulding et al. 2016; Babyk et al. 2018b). However, the relation is fully consistent with the ones obtained using group-only samples (Sun 2012; Bharadwaj et al. 2015). The results for all these linear correlations ($Y = AX^B$; in log space) viz.,

\[ L_X \propto T_X^{3.1 \pm 0.5}, \quad M_{\text{gas}} \propto T_X^{2.6 \pm 0.5}, \quad f_{\text{gas}} \propto T_X^{3.6 \pm 0.5}, \quad Y_X \propto T_X^{3.6 \pm 0.5}, \]

\[ L_X \propto T_X^{3.1 \pm 0.5}, \quad M_{\text{gas}} \propto T_X^{2.6 \pm 0.5}, \quad f_{\text{gas}} \propto T_X^{3.6 \pm 0.5}, \quad Y_X \propto T_X^{3.6 \pm 0.5}, \]

were obtained from the best-fitting relations using the $\text{linmix}$ package.
Figure 2. The profiles of temperature (top left), density (top right), entropy (bottom left), and cooling time (bottom right) for the full sample (see Section 3.2). The red (solid), green (dashed–dotted), blue (dashed), and orange (dotted) lines denote the cool gas free, nuclear cool gas, extended cool gas, and unsure systems, respectively. The black line shows the median profile for the full sample and the grey shaded regions show the median absolute deviation (MAD) spreads about the medians.

The large scatter seen in the thermodynamic profiles is consistent with the short duty cycles (proportional to the cooling time at \( r < 0.1 R_{500} \); Gaspari & Śadowski 2017) predicted by the CCA-regulated feedback in early-type galaxies. As suggested by NGC 6868, the few low-density (high-entropy) outliers with cool gas can be understood by the fact that they might possess significant rotation. This was also observed in the massive lenticular galaxy NGC 7049 that has a high central entropy, despite having a cool H\(\alpha\)+[N II] disc (see Juráňová et al. 2018). Rotation can strongly reduce the SMBH accretion rate (Gaspari et al. 2015), inducing a long-term accumulation of cold/warm gas in the central region or in an extended disc, thus making the multiphase state uncorrelated with the current hot halo properties. The presence of rotational support can decrease the gravitational potential depth and hence, the X-ray surface brightness. This has also been observed in simulations. Based on 2D high-resolution hydrodynamic simulations of early-type galaxies, Negri et al. (2014) found that the hot X-ray emitting gas in fast-rotating galaxies has a systemically lower surface brightness than the hot gas in the non-rotating systems of similar masses. The effect has also been found in some other stud-
Multiphase gas & AGN feedback in giant ellipticals

Figure 3. The combined radially binned profiles of temperature (top left), density (top right), entropy (bottom left), and cooling time (bottom right) for the full sample (see Section 3.2). The red (solid), green (dashed–dotted), and blue (dashed) lines show median profiles for the cool gas free, nuclear cool gas, and extended cool gas systems, respectively, and the shaded regions show the MAD spreads about the medians. The figure shows higher densities and lower entropies and cooling times for the extended cool gas galaxies than the rest of the sample, outside the innermost regions (∼2 kpc).

Table 2. Results of the linear correlation analysis, discussed in Section 4.1, for the 0.5–7.0 keV X-ray luminosities ($L_{X}$; in erg s$^{-1}$), the total gas masses ($M_{\text{gas}}$; in $M_{\odot}$), the gas mass fractions ($f_{\text{gas}}$), and the $Y_{X}$ ($=M_{\text{gas}}T_{X}$; in $M_{\odot}$ keV) values, estimated from within a radius of 10 kpc with the gas temperatures ($T_{X}$; in keV) determined from the same region (results also shown in Fig. 1).

| Relation | Intercept | Slope | Corr. Coeff. |
|----------|-----------|-------|--------------|
| $L_{X} \sim T_{X}$ | $(3.1 \pm 0.5) \times 10^{41}$ | $3.1 \pm 0.5$ | $0.67 \pm 0.09$ |
| $M_{\text{gas}} \sim T_{X}$ | $(1.7 \pm 0.3) \times 10^{9}$ | $2.6 \pm 0.5$ | $0.63 \pm 0.10$ |
| $f_{\text{gas}} \sim T_{X}$ | $0.005 \pm 0.001$ | $1.6 \pm 0.5$ | $0.48 \pm 0.13$ |
| $Y_{X} \sim T_{X}$ | $(1.7 \pm 0.3) \times 10^{9}$ | $3.6 \pm 0.5$ | $0.75 \pm 0.07$ |

Using numerical simulations it has been found that thermal instability is only significant when the cooling time of the gas is less than ∼10 free-fall times (see McCourt et al. 2012; Sharma et al. 2012; Gaspari et al. 2012, 2013; Meece, O’Shea & Voit 2015). We calculated the profiles of free-fall time for all our galaxies as $t_{ff} = r \sigma_{c} / 6\pi g$, where the acceleration due to gravity $g = d\phi/dr = 2\sigma_{c}^{2}/r$ (assuming an isothermal sphere potential $\phi = 2\sigma_{c}^{2} \log(r) + \text{const.}$), leading to $t_{ff} = r \sigma_{c} / 6\pi g$; where $\sigma_{c}$ is the mean central velocity dispersion obtained from the Hyperleda data base (Makarov et al. 2014).\(^{3}\)

The $t_{cool}/t_{ff}$ profiles of the individual galaxies are shown in Fig. A6. The $t_{cool}/t_{ff}$ profiles and the minimum values of $t_{cool}/t_{ff}$, for the full sample are shown in the top left and bottom panels of Fig. 4, respectively. In the top right-hand panel we also show the median $t_{cool}/t_{ff}$ profiles of the cool gas free (red solid lines), nuclear cool gas (green dashed–dotted lines), and extended cool gas (blue dashed lines) groups with the shaded regions showing the MAD about the median profiles. The figure shows that galaxies with cool gas emission (extended+nuclear) have in general, lower values of

\(^{3}\)We also tried calculating $g$ assuming hydrostatic equilibrium, $g = -\rho^{-1} dP/dr$ ($\rho$ = gas mass density = $\mu m_{p}$; $\mu = 0.62$; $m_{p}$ = proton mass), obtained using smooth empirical fits to the pressure profiles. The contribution of non-thermal pressure in a small subsample of galaxies was checked by implementing the approach used in Churazov et al. (2010). We found a maximum non-thermal pressure support of ∼30 per cent. Therefore, for the small radial distances concerned in this paper where the non-thermal pressure can be really significant, we decided to use $g$ obtained using the isothermal sphere potential. We found that using the latter method the $t_{cool}/t_{ff}$ values decrease in the outer regions and increase in the inner regions, although the min($t_{cool}/t_{ff}$) values are only slightly affected.
Figure 4. The $t_{\text{cool}}/t_{\text{ff}}$ profiles of the full sample (top left), the radially binned combined $t_{\text{cool}}/t_{\text{ff}}$ profiles of the different cold gas morphology groups (top right) and the $\min(t_{\text{cool}}/t_{\text{ff}})$ values of the full sample (bottom panel) (see Section 4.1). The red (solid lines/circles), green (dashed–dotted lines/stars), blue (dashed lines/triangles), and orange (dotted lines/diamonds) symbols denote the cool gas free, nuclear cool gas, extended cool gas, and unsure systems, respectively. The black solid lines in the top left-hand panel, and the red (solid), green (dashed–dotted) and blue (dashed) lines in the top right-hand panel show the median profiles for the full sample, and the cool gas free, nuclear cool gas, and extended cool gas galaxies, respectively. The shaded regions show the MAD spreads about the medians. The presence of cool gas seems to be preferred in systems with lower values of $\min(t_{\text{cool}}/t_{\text{ff}})$.

$\t_{\text{cool}}/t_{\text{ff}}$ than the cool gas free galaxies (red), especially outside the innermost regions ($\sim 3$ kpc). There seems to be a separation in the $t_{\text{cool}}/t_{\text{ff}}$ values of the cool gas rich (nuclear and extended) galaxies and the cool gas free galaxies outside $\sim 3$ kpc. Also, the $t_{\text{cool}}/t_{\text{ff}}$ profiles of the extended cool gas galaxies seem to be flatter in the 3–10 kpc range as compared to the nuclear cool gas and cool gas free galaxies for which the values seem to be increasing with radius.

4.1.3 Distributions of cooling instability criteria

We fitted power-law models to the entropy profiles ($K = K_{10} (r/10)^{\alpha_K}$) of all the galaxies in the radial range of 1–30 kpc. A histogram of the entropies of the individual galaxies at 10 kpc ($K_{10}$) obtained from the fits, is shown in the top left-hand panel of Fig. 5. The histogram shows that the galaxies with extended emission line nebulae have lower $K_{10}$ values than the cool gas free galaxies. However, there are outliers and we do not see a clear demarcation in the entropy between the galaxies with and without ongoing cooling, which is also expected because of the short duty cycles of these galaxies. The mean±sigma $K_{10}$ values obtained from a Gaussian fitting of the $K_{10}$ histograms obtained for the cool gas free and the extended cool gas groups were $34 \pm 10$ keV cm$^2$ and $24 \pm 7$ keV cm$^2$, respectively. The top right-hand panel of Fig. 5 shows histograms of the minimum values of $t_{\text{cool}}/t_{\text{ff}}$ obtained for the cool gas free and cool gas rich (extended+nuclear cool gas) groups, which show a similar trend as the entropy. The mean±sigma $\min(t_{\text{cool}}/t_{\text{ff}})$ values obtained from Gaussian fitting of the histograms obtained for the cool gas free and cool gas rich (extended+nuclear) groups were $36 \pm 13$ and $29 \pm 16$, respectively.

According to Voit et al. (2017), the formation of cooling instabilities also depends on the slopes of entropy profiles. The histograms of the slopes $\alpha_K$, of the best power-law fits to the entropy distributions of the cool gas free and extended cool gas groups are shown.

MNRAS 481, 4472–4504 (2018)
in the bottom left-hand panel of Fig. 5. The separation of the two groups appears much weaker here than for the other parameters. The mean±sigma $\alpha_K$ values obtained from Gaussian fitting of the histograms for the cool gas free and extended cool gas groups were $0.86 \pm 0.20$ and $0.75 \pm 0.20$, respectively.

McNamara et al. (2016), Gaspari & Sadowski (2017), and Gaspari et al. (2018) argue that uplift and turbulent motions promote non-linear condensation. To estimate the disturbedness in our systems, which might be an indication of the level of gas motions, we did the following. We first produced 0.5–7.0 keV exposure-corrected images for all the galaxies. Point sources were detected, removed and the empty regions were filled with the average counts from the neighboring pixels. The images were then smoothed with Gaussians of 3 pixel (~1.5 arcsec) width and were fitted with 2D double $\beta$-models in the CIAO Sherpa package. As a proxy for the gas motions (Gaspari & Churazov 2013; Zhuravleva et al. 2014; Hołlmann et al. 2016), we use the root-mean-square (RMS) fluctuations of the residual images within the central 5 kpc regions.

The histograms of the RMS fluctuations obtained for the cool gas rich (extended+nuclear) and cool gas free galaxies, are shown in the right bottom panel of Fig. 5. Although the plot does not show a clear demarcation value of RMS fluctuations between the cool gas rich and free galaxies, it can be seen that in general, the formation of cooling instabilities is preferred in galaxies with higher RMS fluctuations. We also tried the scales at 2.5 kpc and 10 kpc. The distinction between cool gas free and cool gas rich galaxies seems to get better at smaller scales (2.5 kpc) and almost disappears at larger scales (10 kpc). The mean±sigma 5 kpc RMS fluctuations obtained from the Gaussian fitting to the histograms for the cool gas free and cool gas rich (extended+nuclear) groups was found to be $0.02 \pm 0.01$ and $0.03 \pm 0.02$, respectively. Note that the value of the RMS fluctuation has some dependence also on the depth of the data and the pixel scale, and the line-of-sight projection effects also complicate these measurements.

We also checked if the $K_{10, \text{min}}(t_{\text{cool}}/t_{\text{ff}})$, $\alpha_K$ and RMS fluctuations obtained for the cool gas rich and cool gas poor galaxies statistically belong to two different populations. For this we used Welch’s $t$-test where $t$ is defined as

\[
t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}}\]

where $\overline{X}_1$ and $\overline{X}_2$ are the means, $S_1^2$ and $S_2^2$ are the variances, and $n_1$ and $n_2$ are the sizes of the two samples $X_1$ and $X_2$. The test is based on the null hypothesis that the samples have been taken from the same parent distribution. The $t$ values so obtained and the corresponding null hypothesis probabilities ($p$ for $n_1 + n_2 - 2$ degrees of freedom), for the $K_{10, \text{min}}(t_{\text{cool}}/t_{\text{ff}})$, $\alpha_K$ and RMS fluctuations obtained for the extended cool gas (ECG), Nuclear cool gas (NCG), and Cool gas free (CGF) groups, using different combinations (viz., ECG versus CGF, ECG+NCG versus CGF, and ECG versus NCG+CGF)
of the three groups, are given in Table 3. The histograms of $K_{10}$, \(\text{min}(t_{\text{cool}}/t_{\text{jet}})\), $\alpha_K$ and RMS fluctuations corresponding to only the best combination (highest $t$, lowest $p$) are shown in Fig. 5. We find that the distributions of $K_{10}$, \(\text{min}(t_{\text{cool}}/t_{\text{jet}})\), $\alpha_K$ and the RMS fluctuations of the cool gas rich and cool gas free galaxies are different at $>99$ per cent, 91 per cent, 87 per cent, and 98 per cent confidence levels, respectively.

### 4.2 Feedback cycles

To investigate the connection between the cool gas and AGN activity, we search for a correlation between the AGN jet power and the $\text{H}\alpha+[\text{N II}]$ luminosities of the galaxies. The jet powers ($P_{\text{jet}}$) are calculated as the work required to inflate a cavity with a volume $V$ divided by the age of the cavity, $P_{\text{jet}} = 4PVT_{\text{age}}$. $P$ is the pressure of the hot gas determined from the X-ray observations. Cavities are usually approximated as ellipsoids and their sizes are estimated either from the X-ray images (Cavagnolo et al. 2010; Russell et al. 2013) or from the radio lobes (Allen et al. 2006). The ages of cavities are either assumed to be their buoyancy rise times or sound crossing times $r/c_s$ (where $r$ is the distance of the cavity from the centre and $c_s$ is the sound speed).

Due to the inconsistencies in the $P_{\text{jet}}$ estimates available in the literature, we recalculated these values for 15 of the 21 galaxies in our sample that host clear cavities. The sizes for all these cavities (except for NGC 4649) were taken from a single source (Shin, WenHao & Mulchaey 2016). For NGC 4649, we used the X-ray cavity size given in Paggi et al. (2014). The cavity volumes and the associated uncertainties were calculated as described in Birzan et al. (2004). The ages of the cavities were estimated as their buoyancy rise times. For the remaining six galaxies with cavities, we used the estimates given in Cavagnolo et al. (2010), as their method of calculating jet powers is similar to ours. The jet powers for the 21 galaxies are given in Table 4.

Fig. 6 shows the jet powers for the 21 galaxies as a function of their $\text{H}\alpha+[\text{N II}]$ luminosities. For six of the 21 galaxies, the $\text{H}\alpha+[\text{N II}]$ luminosities were obtained from Macchetto et al. (1996); five of these were detected as small disc emission. Also, there were three more galaxies for which $\text{H}\alpha+[\text{N II}]$ flux estimates were available in the literature but no $\text{H}\alpha+[\text{N II}]$ emission was detected in the SOAR/APO observations. As discussed in Section 2.1, the $\text{H}\alpha+[\text{N II}]$ luminosities for these eight sources should be interpreted as upper limits. We find a weak positive correlation (Pearson’s coefficient $\sim 0.38$) between the two quantities, which reduces to $\sim 0.24$, if the eight galaxies with upper limits are excluded. From Fig. 6, in general, the jet power seems to be increasing with the $\text{H}\alpha+[\text{N II}]$ luminosities (bigger circles represent more extended $\text{H}\alpha+[\text{N II}]$ emission). The red, green, blue, and orange colours denote the cool gas free, nuclear cool gas, extended cool gas, and unsure systems, respectively. There seems to be a weak positive correlation between the AGN jet powers of the galaxies and their $\text{H}\alpha+[\text{N II}]$ luminosities.

![Figure 6](https://academic.oup.com/mnras/article-abstract/481/4/4472/5104394)

Figure 6. Jet powers of the 21 galaxies with X-ray cavities versus their $\text{H}\alpha+[\text{N II}]$ luminosities. The red, green, blue, and orange colours denote the cool gas free, nuclear cool gas, extended cool gas, and unsure systems, respectively. There seems to be a weak positive correlation between the AGN jet powers of the galaxies and their $\text{H}\alpha+[\text{N II}]$ luminosities.
for the jet power in this system from O’Sullivan et al. (2011) (cavity sizes estimated using radio lobes). With this, we find a weak positive correlation (Pearson’s coefficient $\sim 0.19$) between the two quantities which reduces to $\sim 0.04$, if the eight galaxies with upper limits are excluded.

The large scatter in the jet powers and the H $\alpha$+[N II] luminosities, the positive correlation between the two, and the increase of jet power with the cool gas extent, hint towards the scenario of hysteresis cycles driven by CCA, which has been shown via high-resolution 3D hydrodynamical simulations to be the most consistent mechanism for self-regulating AGN feedback in Early Type Galaxies (ETGs) (Gaspari et al. 2013, 2015, 2018) and brightest cluster galaxies (Gasparrini et al. 2012a,b; Prasad et al. 2015; Voit et al. 2017). Simply put, during CCA, the higher the condensed gas mass (thus higher $L_{41\alpha} \propto M_{\text{cool}} c^2$; more below). On top of this trend, the intrinsically chaotic evolution of the colliding clouds/filaments in CCA drives a substantial ($\sim 1$ dex) variability which can hinder a strong linear correlation (yet preserving a positive Pearson coefficient). Furthermore, the correlation between $P_{\text{jet}}$ and cool gas luminosity (thus condensation) is consistent with the turbulent eddy criterion (Section 1), as larger jet powers imply larger turbulent velocity dispersions (from the turbulent energy flux rate, $\sigma_\tau \propto P_{\text{jet}}^{1/3}$) and hence larger RMS surface brightness fluctuations (as found in Section 4.1.3). We note that alternative models as hot/Bondi accretion would instead have negligible variability and show no correlations with the cool phase (nor turbulence). Needless to say, forthcoming investigations should significantly expand the ETG sample and achieve more accurate detections in warm gas, which remains one of our main thrusts for our ongoing campaigns.

In more detail, the AGN self-regulation cycle works as follows. In the beginning of the proposed AGN feedback cycle, the galaxies have, in general, weak gas motions and smooth and symmetric X-ray morphologies. Galaxies in this phase have neither cold gas nor central AGN jets but may have high central entropies as a result of past AGN activity. As the gas in the central regions of the galaxies cools, the entropy decreases and the cooling instabilities start forming, giving rise to the cold gas filaments. As the cold gas accretion increases, the AGN jet power also increases and the powerful jets start interacting with the surrounding medium, driving large-scale gas motions and inflating X-ray cavities. The gas motions further increase the formation of cooling instabilities. Eventually, the jets start heating the surrounding medium,\(^6\) preventing further formation of cold gas and might also destroy the existing cold gas filaments. The cold gas fuel further reduces due to the AGN jet interaction and the galaxies might then be left with just nuclear cold gas with some AGN activity. Finally due to the lack/absence of cold gas fuel, the AGN starves, the jet activity stops and the galaxy returns to its initial phase.

As also discussed in Section 4.1, it is important to note that the feedback cycles in early-type galaxies are much faster (a few 10s Myr) compared to massive clusters (several 100s Myr). Note also how the cooling rate $M_{\text{cool}} \propto L_X/T_X$ is relatively larger in massive ETGs because of line cooling ($< 1$ keV) and the $T_X^{-1}$ dependence. This implies a much more pronounced hysteresis in the early-type galaxies, with high/low feeding and feedback states less separated and more intertwined, as found in the current observational study.

Based on an analysis of 107 galaxies, groups and clusters, McDonald et al. (2018) found that the correlation between the mass cooling rate of the ICM and the star formation rate breaks down at the low-mass end, suggesting that the cold gas and star formation are mainly being driven by stellar mass-loss for the low-mass systems. However, in our sample, majority of which includes massive ETGs with extended haloes, we see clear separations in the density, entropy, and cooling time profiles in the 2–35 kpc radial range, based on the multiphase gas presence. These are clear signs of large-scale condensation.

Elliptical galaxies, groups and poor clusters of galaxies are the building blocks of massive clusters and are therefore crucial for understanding the cosmic structure formation in the Universe. Moreover, X-ray haloes are of key importance and appear to be ubiquitous, not only for massive ETGs but even for compact or fossil ETGs (Werner et al. 2018). As of now, most of the studies centred on the non-gravitational processes (cooling, AGN feedback etc.) focus only on the bright massive clusters since the current X-ray missions are limited in their capability to study the X-ray emission in the fainter low-mass systems out to $R_{500}$. The future Athena X-ray observatory will allow us to extend the studies of hot haloes in giant elliptical galaxies out to redshift $z \sim 1$, allowing us to investigate the various details (source, effect mass dependence, time-scales etc.) of the non-gravitational processes (Ettori et al. 2013; Roncarelli et al. 2018).

### 5 CONCLUSIONS

We have analysed Chandra X-ray observations of a sample of 49 nearby X-ray and optically bright giant elliptical galaxies. In particular, we focus on the connection between the properties of the hot X-ray emitting gas and the cooler H $\alpha$+[N II] emitting phase, and the possible role of the cool phase in the AGN feedback cycle. Our main findings are summarized as follows:

(i) We do not find a correlation between the presence of H $\alpha$+[N II] emission and the X-ray luminosity, mass of hot gas, and gas mass fraction.

(ii) The observed correlation between the gas mass fractions and the X-ray temperatures suggests that the cores of hotter, more massive systems are able to hold on to a larger fraction of their X-ray emitting gas.

(iii) We find that the presence of H $\alpha$+[N II] emission is more likely in systems with higher densities, lower entropies and cooling times (outside the innermost regions) shallower entropy profiles, lower values of $\text{min}(t_{\text{cool}}/t_{\text{H}})$, and more disturbed X-ray morphologies.

(iv) The distributions of the thermodynamic properties of the nuclear cool gas galaxies are found to be in between the extended cool gas and cool gas free galaxies.

(v) We find that the distributions of entropies at 10 kpc, the $\text{min}(t_{\text{cool}}/t_{\text{H}})$ values, the slope of the entropy profiles ($\sigma_\tau$) and the RMS surface-brightness fluctuations within a radius of 5 kpc are statistically different between cool gas rich and cool gas free galaxies at $\sim 99$ per cent, 91 per cent, 87 per cent, and 98 per cent confidence levels, respectively.

(vi) The large scatter and the significant overlap between the properties of systems with and without optical emission line nebulae indicate rapid transitions from one group to the other. The continuous distribution might also be a result of the chaotic nature
and rapid variability of the feeding and feedback cycle in these systems. (vii) The AGN jet power of the galaxies with X-ray cavities hint towards a positive correlation with their Hα+[N II] luminosity. This feature, the presence of cool gas in more disturbed/turbulent haloes, and frequent hysteresis cycles in ETGs are consistent with a cold gas nature of AGN feeding and related CCA scenario.

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### Table A1. A log of the *Chandra* observations used in the paper.

| Name (ks) | Observation (ks) | Instrument | Cleaned Exposure (ks) | Date of Observation |
|-----------|------------------|------------|-----------------------|---------------------|
| NGC 449   | 1177             | ACIS-S     | 45.29                 | 2010-09-14          |
| IC 1880   | 10537            | ACIS-S     | 31.12                 | 2009-09-12          |
| IC 4296   | 2021             | ACIS-S     | 14.20                 | 2001-09-10          |
| NGC 57    | 10547            | ACIS-S     | 8.89                  | 2008-10-29          |
| NGC 315   | 4166             | ACIS-S     | 37.45                 | 2003-02-22          |
| NGC 410   | 5897             | ACIS-S     | 2.05                  | 2004-11-30          |
| NGC 499   | 2882             | ACIS-I     | 40.13                 | 2002-01-08          |
| NGC 507   | 2882             | ACIS-I     | 40.13                 | 2002-01-08          |
| NGC 533   | 2880             | ACIS-S     | 36.36                 | 2002-07-17          |
| NGC 708   | 7921             | ACIS-S     | 105.53                | 2006-11-20          |
| NGC 741   | 17198            | ACIS-S     | 70.94                 | 2015-12-04          |
| NGC 751   | 18718            | ACIS-S     | 48.36                 | 2015-12-06          |
| NGC 1316  | 5021             | ACIS-I     | 7.81                  | 2004-12-23          |
| NGC 1399  | 41529            | ACIS-S     | 29.31                 | 2015-11-06          |
| NGC 1404  | 17549            | ACIS-S     | 60.63                 | 2015-03-28          |
| NGC 1407  | 14033            | ACIS-S     | 45.29                 | 2012-06-17          |
| NGC 1521  | 10939            | ACIS-S     | 43.52                 | 2009-07-04          |
| NGC 1550  | 3186             | ACIS-I     | 9.22                  | 2002-01-08          |
| NGC 1600  | 4371             | ACIS-S     | 9.13                  | 2002-01-08          |
| NGC 2300  | 4371             | ACIS-S     | 20.90                 | 2002-03-12          |
| NGC 2030  | 10939            | ACIS-S     | 29.31                 | 2015-11-06          |
| NGC 5013  | 3215             | ACIS-S     | 22.51                 | 2003-02-13          |
| NGC 523   | 1563             | ACIS-S     | 18.24                 | 2006-11-16          |
| NGC 4782  | 3220             | ACIS-S     | 39.16                 | 2002-06-16          |
| NGC 4936  | 4997             | ACIS-I     | 10.23                 | 2004-02-09          |
| NGC 5044  | 798              | ACIS-S     | 17.91                 | 2003-03-19          |
| NGC 5129  | 7325             | ACIS-I     | 21.74                 | 2006-05-14          |
| NGC 5613  | 9157             | ACIS-S     | 88.25                 | 2006-05-05          |
| NGC 5204  | 1620             | ACIS-S     | 26.85                 | 2003-02-13          |
| NGC 4782  | 3220             | ACIS-S     | 39.16                 | 2002-06-16          |
| NGC 5129  | 7325             | ACIS-I     | 21.74                 | 2006-05-14          |
| NGC 5613  | 9157             | ACIS-S     | 88.25                 | 2006-05-05          |
| NGC 5204  | 1620             | ACIS-S     | 26.85                 | 2003-02-13          |
| NGC 5013  | 3215             | ACIS-S     | 22.51                 | 2003-02-13          |
| NGC 4782  | 3220             | ACIS-S     | 39.16                 | 2002-06-16          |
| NGC 5129  | 7325             | ACIS-I     | 21.74                 | 2006-05-14          |
| NGC 5613  | 9157             | ACIS-S     | 88.25                 | 2006-05-05          |
| NGC 5204  | 1620             | ACIS-S     | 26.85                 | 2003-02-13          |
Figure A1. Deprojected temperature profiles of the individual galaxies.
Figure A1 – continued
Figure A1 – continued
Figure A2. Deprojected density profiles of the individual galaxies.
Figure A2 – continued
Figure A3. Deprojected entropy profiles of the individual galaxies.
Figure A3 – continued

$K$ (keV cm$^2$)

NGC1407  NGC1521  NGC1550

NGC1600  NGC2300  NGC2305

NGC3091  NGC3923  NGC4073

NGC4125  NGC4261  NGC4374

NGC4406  NGC4472  NGC4486

NGC4552  NGC4636  NGC4649

Radius (kpc)

$10^0$  $10^1$  $10^2$  $10^3$  $10^4$  $10^5$
Figure A3 – continued
Figure A4. Deprojected pressure profiles of the individual galaxies.
Figure A4 – continued
Figure A4 – continued
Figure A5. Cooling time profiles of the individual galaxies.

MNRAS 481, 4472–4504 (2018)
Figure A5 – continued
Figure A5 – continued
Figure A6. $t_{\text{cool}}/t_{\text{ff}}$ profiles of the individual galaxies.
Figure A6 — continued

Multiphase gas & AGN feedback in giant ellipticals

MNRAS 481, 4472–4504 (2018)
Figure A6 – continued

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