Galaxy Evolution and Feedback across Different Environments
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Supermassive Black Hole feedback in early type galaxies

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Abstract. Optically luminous early type galaxies host X-ray luminous, hot atmospheres. These hot atmospheres, which we refer to as *coronae*, undergo the same cooling and feedback processes as are commonly found in their more massive cousins, the gas rich atmospheres of galaxy groups and galaxy clusters. In particular, the hot coronae around galaxies radiatively cool and show cavities in X-ray images that are filled with relativistic plasma originating from jets powered by supermassive black holes (SMBH) at the galaxy centers. We discuss the SMBH feedback using an X-ray survey of early type galaxies carried out using Chandra X-ray Observatory observations. Early type galaxies with coronae very commonly have weak X-ray active nuclei and have associated radio sources. Based on the enthalpy of observed cavities in the coronae, there is sufficient energy to "balance" the observed radiative cooling. There are a very few remarkable examples of optically faint galaxies that are 1) unusually X-ray luminous, 2) have large dark matter halo masses, and 3) have large SMBHs (e.g., NGC4342 and NGC4291). These properties suggest that, in some galaxies, star formation may have been truncated at early times, breaking the simple scaling relations.

Keywords. galaxies: elliptical and lenticular, cD X-rays: galaxies, galaxies: jets, galaxies: evolution

1. Early type galaxies in the family of dark matter halos

Across the range of dark matter halo masses, massive early type galaxies often lie at the centers of gas rich atmospheres (see Fig. 1 for two prominent examples of gas rich atmospheres around individual early type galaxies). From brightest cluster galaxies (BCGs) in massive clusters to groups and individual galaxies, central galaxies with supermassive black holes (SMBHs) play an important role (see contribution from C. Jones in this volume for a discussion of more massive systems). With the discovery of the X-ray bright atmospheres, the problem of preventing over cooling and massive amounts of star formation became an important focus of study. Early studies argued that many clusters, with high central gas densities, should have gas cooling and settling on the central galaxies (e.g., Fabian & Nulsen 1977). These were the so-called "cooling flows". Despite careful searches for cool gas or newly formed stars, the predicted amounts of material remained undetected (Fabian 1994).

Only at the turn of the millennium did the first hints of a robust solution to the problem begin to appear with the comparison of high angular resolution X-ray and radio

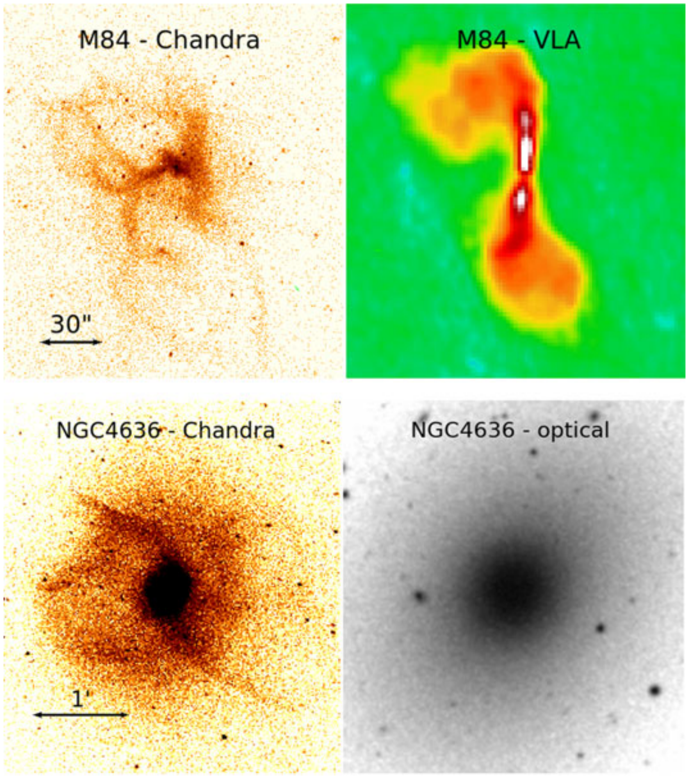

Figure 1. Examples of feedback in early type galaxies from active galactic nuclei (AGN). (top) The Chandra and VLA images (at matched scales) of M84 = NGC4374 showing the very disturbed X-ray atmosphere surrounding the galaxy and the corresponding radio image. The radio plasma fills the large northern and southern cavities in the X-ray surface brightness (see Finoguenov *et al.* 2008 for more details). (bottom) Chandra and digital sky survey images (at matched scales) of NGC4636. The Chandra image shows the very disturbed X-ray atmosphere surrounding this otherwise optically "normal" galaxy (see Baldi *et al.* 2009 for more details).

observations (Böhringer *et al.* 1993; Churazov *et al.* 2000, 2001; McNamara *et al.* 2000; Fabian *et al.* 2000). These analyses showed that supermassive black holes (SMBH) at the centers of X-ray bright atmospheres were radiatively faint, but mechanically powerful. In this new paradigm, SMBHs drive jets that inflate buoyant bubbles of relativistic plasma which appear as cavities in cluster, group, and galaxy X-ray images (see reviews Fabian 2012; Bykov *et al.* 2015; Werner *et al.* 2019). In fact, the power required to inflate the bubbles is sufficient to compensate for the radiative cooling (e.g., Bîrzan *et al.* 2004). The detailed mechanism for transferring the bubble energy to the hot gas remains a topic of intense discussion, but one very strong candidate is turbulent motion of the hot gas as the buoyant bubbles rise in the hot atmospheres (see Zhuravleva *et al.* 2014).

In this contribution, we focus on the lower end of the mass scale of the family of dark matter halos. Hot galactic coronae were first detected from Einstein Observatory observations (Forman *et al.* 1979, 1985; Nulsen *et al.* 1984). As in more X-ray luminous systems, early type galaxies have short cooling times and, in the absence of a heating mechanism, are expected to be the sites of significant star formation (Thomas *et al.* 1986). Although the feedback process in single galaxies is not as powerful as in rich galaxy clusters, the signatures of AGN feedback - cavities in the X-ray gas distribution, filled with relativistic plasma from the SMBH - are commonly seen (see Fig. 1 for examples of

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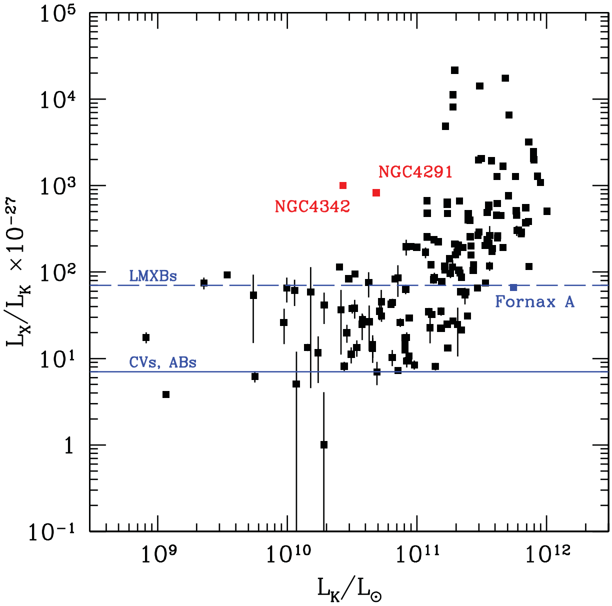

Figure 2. The X-ray luminosity (ergs sec^{-1}) of galaxies per unit K-band luminosity (in solar luminosities) plotted vs. K-band luminosity from a large sample of galaxies, observed with the Chandra X-ray Observatory. The figure shows that luminous systems (in the K-band, a good proxy for mass; Bell *et al.* 2003), which typically have massive dark matter halos, are able to contain the hot gas, although they do exhibit a wide range of luminosity. At fainter optical luminosities, the galaxies are X-ray faint and likely drive galactic winds. Three labeled galaxies are discussed in the text. Although the sample excludes brightest cluster galaxies (BCGs), galaxies in groups are included. The two horizontal lines show the predicted contribution from low mass X-ray binaries (LMXBs) and cataclysmic variables and active stellar systems (ABs). In the survey, when exposures are sufficiently deep, any detected LMXBs are excluded.

bubbles and cavities in galaxy scale dark matter halos; see Jones & Forman, this volume, for a discussion of feedback in M87).

2. Chandra survey of early type galaxies

Fig. 2 shows the X-ray luminosity of galaxies per unit K-band luminosity plotted vs. K-band luminosity from a large sample, observed with the Chandra X-ray Observatory, that excludes galaxy clusters but does include galaxies at the centers of poor galaxy groups (e.g., NGC4636; see Fig. 1). This sample was taken from observations of optically bright galaxies that were targeted by Chandra. As a class, luminous early type galaxies (brighter than $L_K{\sim}10^{11}$ $L_\odot$) are also luminous in X-rays. At a given L_K, the figure shows that the galaxies display a wide range of X-ray luminosity. Prior to the discovery of hot coronae, early type galaxies were believed to be gas poor as a result of galactic winds (e.g., Mathews & Baker 1971 and Faber & Gallagher 1976). However, X-ray observations have shown that these galaxies are *not gas poor* systems but have gaseous atmospheres as massive as the interstellar mediums of their spiral galaxy cousins (e.g., Forman *et al.* 1985). In this sample of more than 100 early type galaxies, 70% of the galaxies have radio sources associated with their nuclei. In addition, about 80% of the galaxies have X-ray bright sources located within a few arcseconds of the galaxy center. These nuclear sources have luminosities ranging from $\sim 10^{38}-10^{42}$ ergs s^{-1}. Using a simple scaling relation of K-band luminosity to stellar mass and stellar mass to SMBH mass, we can derive the Eddington ratios for the active nuclei. We find $L_x/L_{edd}{\sim}10^{-5}-10^{-9}$. Hence, these are

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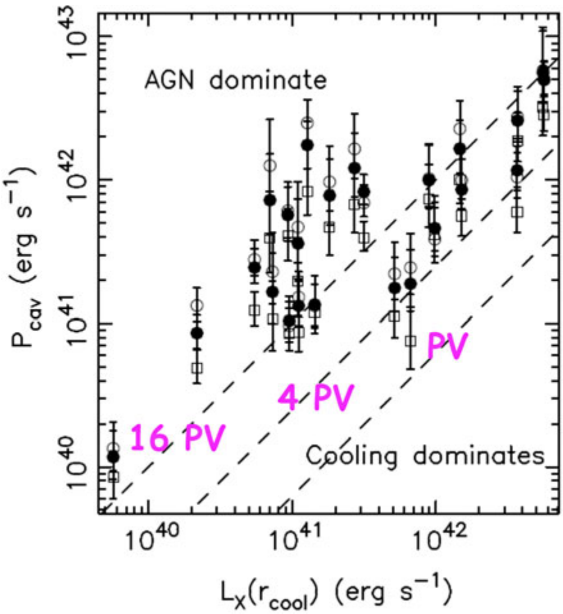

Figure 3. Cavity power vs cooling power for outbursts detected in the Chandra sample (adapted from Nulsen *et al.* 2009). Filled markers, open circles and open squares show three different estimates of the power using different timescales: P_{sonic}, $P_{buoyancy}$ and P_{refill}, the sonic, buoyancy, and refill timescales, respectively, with 90% confidence ranges. Dashed lines (as labeled) indicate different conversion factors that account for the ratio of the cavity power to the total power injected (see Fig. 8 in Werner *et al.* 2019 for an extension to galaxy clusters).

consistent with radiatively inefficient, but mechanically powerful, SMBH outbursts (for models of this class see, for example: Ichimaru 1977; Rees *et al.* 1982; Yuan & Narayan 2014).

Of the X-ray bright systems, about 30% exhibit X-ray cavities similar to those seen in Fig. 1. The discovery of cavities provides a method for measuring the energy, injected by the jets from SMBHs, into the hot, X-ray emitting gas, as the relativistic plasma inflates cavities. By measuring the pressure, P, and volume, V of the cavities, the PV work could be computed (Churazov *et al.* 2000). First for galaxy clusters and then for groups, studies of cavities provided convincing evidence that the SMBH feedback was sufficient to dramatically reduce the cooling of the X-ray emitting atmospheres (see for example, Bîrzan *et al.* 2004 and Fig. 5 of Fabian 2012).

On galaxy scales too, the cavities were shown to provide sufficient energy to “balance” cooling. Fig. 3 (adapted from Nulsen *et al.* 2009) shows that for many optically and X-ray luminous galaxies, the cavity power is sufficient to balance radiative cooling. The analysis uses three estimates to derive the cavity timescale. These three timescales are 1) the sonic timescale, the sound crossing time, 2) the buoyancy time, the time for the buoyant bubble to rise to its present position at the buoyant terminal speed, and 3) the refill time, the time for the observed volume to be refilled as the bubble rises. Fig. 3 shows all three estimates for 24 galaxies observed with Chandra. These estimates of the power are plotted vs. the cooling luminosity (for details see Nulsen *et al.* 2009). Three diagonal, dashed lines are drawn where the cavity power and the cooling luminosity are equal, with the cavity power assumed to be PV, $4PV$, or $16PV$. Note that jets could, and sometimes do, inflate bubbles supersonically which drives shocks into the surrounding gas, providing additional energy beyond just the work required to inflate the bubbles (for example, see

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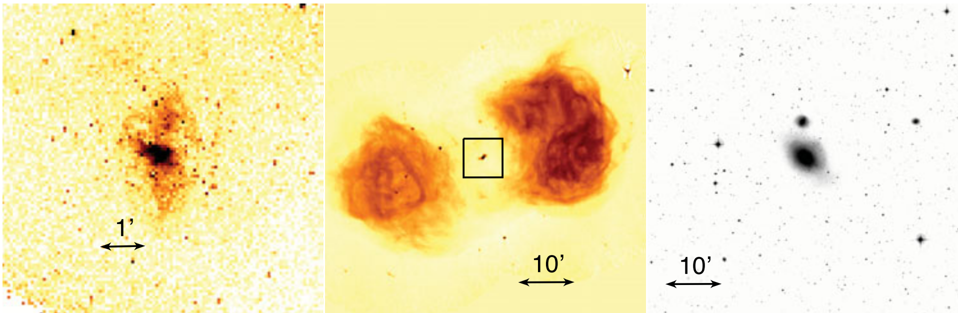

Figure 4. Chandra, VLA, and optical images of Fornax A (NGC1316). Note the very different scale of the Chandra image compared to radio and optical. (left) Chandra image of Fornax A shows a very disturbed gas distribution. Lanz *et al.* (2010) estimate an outburst energy of $\sim 10^{58}$ ergs. The X-ray luminosity is reduced by the outburst that disperses the hot gas from the core, reducing the density and hence the luminosity. (center) 20 cm VLA image (Fomalont *et al.* 1989) showing the large scale radio emission and the central core. The square box at the center delineates the field of view of the Chandra image at left. (right) optical (red) image of NGC1316 at the same scale as the radio image. At a distance of 23 Mpc, $1' = 6.5$ kpc).

Baldi *et al.* 2009; Fabian *et al.* 2000; Forman *et al.* 2017, and Randall *et al.* 2015). For those galaxies with cavities, there is more than sufficient energy to offset radiative cooling. While cavities are not detected in all hot galaxy atmospheres, the cycle of cooling and heating outbursts is irregular, but on average, the SMBHs appear to be balancing radiative cooling.

While the feedback process is very often "balanced", there are notable exceptions on scales from clusters to galaxies. On cluster scales, the Phoenix cluster (McDonald *et al.* 2012), with 800 $M_\odot$ yr^{-1} of star formation, shows a SMBH that has failed to offset cooling. Among the galaxies, Fornax A (labeled in blue in Fig. 2) has one of the lowest X-ray luminosities for its K-band luminosity (a proxy for stellar mass). Fig. 4 shows the X-ray and radio images of Fornax A. The SMBH at the center of the galaxy NGC1316, that hosts Fornax A, has undergone a remarkable outburst and dramatically disturbed the X-ray atmosphere which serves to decrease the X-ray luminosity (since the luminosity depends on the square of the gas density). Detailed multi-wavelength studies (Mackie & Fabbiano 1998 and Lanz *et al.* 2010) have discussed the outburst history and the merger event that occurred in NGC1316 within the last 2 Gyr. Lanz *et al.* (2010) suggest that observed cavities require an outburst energy of $\sim 10^{58}$ ergs. With a massive SMBH, possibly fueled by mergers, SMBHs are capable of dramatically impacting a hot atmosphere.

3. NGC4342 and NGC4291 - optically faint, X-ray bright galaxies

Two remarkable galaxies, NGC4342 and NGC4291, both members of poor groups, are shown in Fig. 2 (see red identifiers). These two galaxies are unusually X-ray luminous for their K-band luminosities (see Bogdán *et al.* 2012 for a detailed discussion of these two galaxies). Both galaxies have dynamically measured SMBH masses (Schulze & Gebhardt 2011; Cretton & van den Bosch 1999) that are 60 and 13 times larger than expected from the mean SMBH mass vs. optical bulge mass relation (given by Häring & Rix 2004). The uniqueness of these galaxies is visually emphasized in Fig. 5 that compares the X-ray and optical properties of several comparable galaxies around NGC4342. Although optical properties are similar, NGC4342 has a remarkable X-ray corona. For both NGC4342 and NGC4291, the X-ray data can be used to derive the total gravititating mass, assuming

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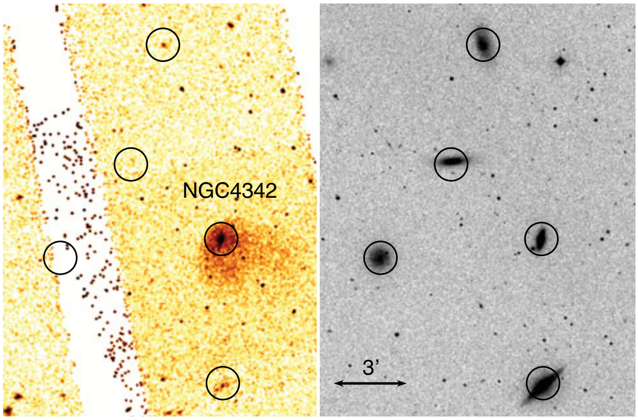

Figure 5. Chandra and optical images of NGC4342 at matched scales. (left) Chandra image of NGC4342 and its surroundings with other optically comparable galaxies that are all members of the W' cloud (Mei *et al.* 2007 and Bogdán *et al.* 2012). (right) Optical image matching the Chandra image. Optical galaxies are circled in both the X-ray and optical images. Clearly, NGC4342 is "special" - of these comparable galaxies, several of which also lie in the Chandra field, only NGC4342 hosts a hot X-ray corona and, therefore, a significant dark matter halo. As described in the text, its SMBH is also unusually massive for the mass of its measured stellar bulge.

hydrostatic equilibrium, which shows they both lie in substantial dark matter halos (10 and 5 times the stellar mass for NGC4342 and NGC4291, respectively; Bogdán *et al.* 2012).

As shown above for Fornax A, SMBHs are capable of powerful outbursts when properly "fed". One possible scenario to create systems like NGC4342 and NGC4291, is for an aggressively growing SMBH to have had an unusually large outburst at an early epoch, before star formation was completed, which prematurely terminated star formation. Some simulations (e.g., Bonoli *et al.* 2014 and Katz *et al.* 2015) suggest that SMBH growth precedes the growth of the stellar mass. If this scenario is correct, then we should expect to see more systems like NGC4342 and NGC4291.

Another class of interesting galaxies that host X-ray bright coronae and massive SMBHs are "relics", the present epoch counterparts of high redshift "red nuggets" (e.g., Buote & Barth 2018, 2019). The variety of hot coronae will provide new insights on galaxy evolution and yield powerful constraints for the growth of SMBHs.

4. Summary and Conclusions

At the low end range of the mass distribution of dark matter halos, early type galaxies host gas rich atmospheres. However, unlike their spiral counterparts, these atmospheres are hot and easily recognizable as extended in X-ray images. Furthermore, like their more massive cousins, groups and clusters, early type galaxies (those brighter than $L_K{\sim}10^{11}$ $L_\odot$) undergo cycles of feedback with outbursts from SMBH's inflating bubbles that provide energy to the radiatively cooling gas. A few rare objects, e.g., NGC4342 and NGC4291, appear to have become overly "enthusiastic", at early epochs, and may have terminated star formation before the stellar mass grew to the characteristic size needed to lie on the stellar mass - SMBH mass relation. New scaling relations (e.g., Bogdán & Goulding 2015; Bogdán *et al.* 2018; Phipps *et al.* 2019, and Gaspari *et al.* 2019) suggest that the stellar mass may not be the fundamental driver of SMBH mass. X-ray all-sky surveys from *eROSITA* will provide large samples of X-ray bright galaxies to fully explore the present epoch population of dark matter halos and their hot gas content.

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