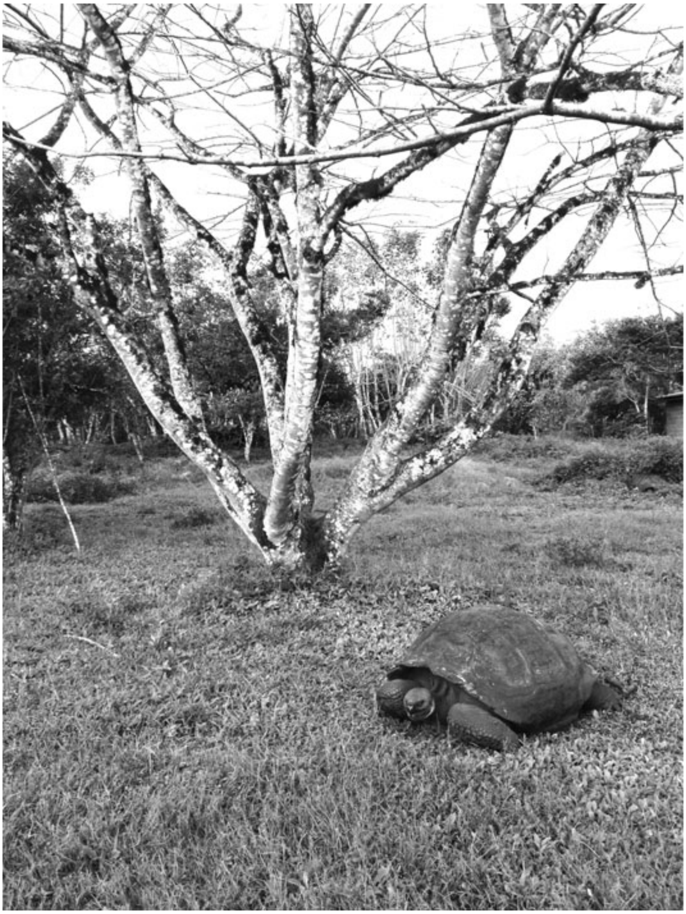
Cosmological Evolution of Jet Progenitors



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Supermassive black holes (SMBH) at work: M87, a case study of the effects of SMBH outbursts

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Abstract. Supermassive black holes (SMBHs) play key roles in galaxy and cluster evolution. This is most clearly seen in the "fossil record" that is imprinted in the gas rich atmospheres of early type galaxies, groups, and clusters by powerful SMBH outbursts. From a detailed X-ray study of M87, we present the properties of a typical SMBH outburst, its evolution, and the energy partition between shocks and the enthalpy of the gas cavities inflated by the SMBH. About 12 Myr ago, the SMBH in M87 inflated a cavity of relativistic plasma which is still centered near the galaxy nucleus. This outburst drove a shock into the surrounding gas. For M87, we show that the outburst duration is a few Myr and that about 50% of the total energy (5×10^{57} ergs) resides in the bubble inflated by the jet from the SMBH, that 25% of the outburst energy is deposited directly into the ambient atmosphere by the shock, and that 25% of the outburst energy is lost from the radiatively bright core as the weak shock moves to large radii. We conclude by describing a future X-ray mission, SMART-X, with $< 1''$ angular resolution that would allow us to study the evolution of SMBHs and the hot, X-ray emitting atmospheres from high redshifts to the present for M87-like systems.

Keywords. X-rays: galaxies, X-rays: galaxies: clusters, galaxies: individual (M87), galaxies: active, galaxies: evolution, galaxies: elliptical and lenticular, cD

1. Introduction

Along with galaxy groups, and galaxy clusters, optically luminous early type galaxies form a family of gas rich systems whose dark matter halos are filled with hot gas having characteristic temperatures ranging from $\sim 1 - 10$ keV (Forman, Jones, & Tucker 1985). A characteristic of this family is gas cooling which, absent any additional energy sources, would produce at least an order of magnitude more cool gas than is observed (e.g., Thomas *et al.* 1986, Fabian 2012). However, the past decade has shown that 1) jets from supermassive black holes in massive galaxies inflate bubbles of relativistic plasma 2) the jet power, as measured by the energy content of bubbles and their ages, is comparable to the energy radiated by the hot atmospheres, and 3) the energy contained in the bubbles

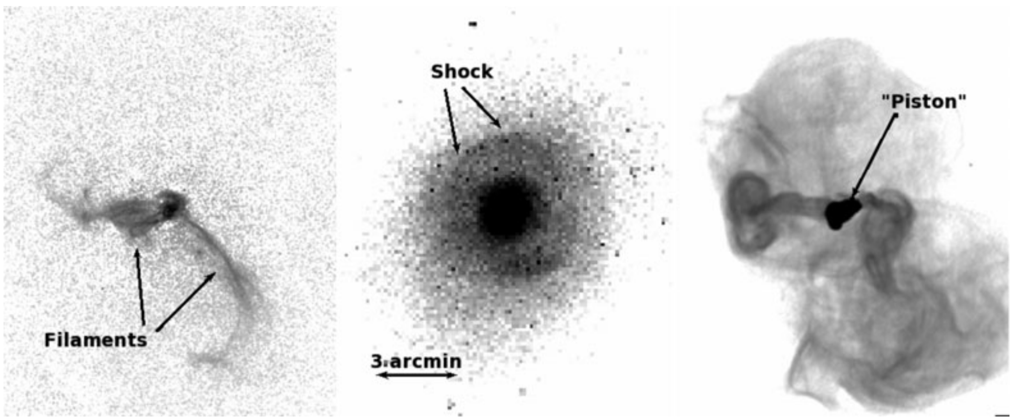

Figure 1. Three images of M87 at the same scale. a) (left) the soft band image (0.5-1.0 keV) of M87 emphasizing the X-ray filamentary structure associated with the eastern radio torus and the southwestern arm (see right panel c); b) (center) the hard (3.5-7.5 keV) band image of M87 showing regions of overpressure and the clear 13 kpc shock that appears as a nearly circular feature; c) (right) the 90 cm radio image of M87 from Owen, Eilek & Kassim (2000) that shows the classic mushroom-shaped torus and stem to the east and the disrupted southwestern arm that entrains the fine X-ray filamentary arm (see left panel a).

is captured and transferred to the radiatively cooling gas in galaxy, group, and cluster cores (e.g., Churazov *et al.* 2000, Churazov *et al.* 2001, Birzan *et al.* 2004, McNamara & Nulsen 2007, Nulsen *et al.* 2009, Fabian 2012) . Most recently, Chandra observations of density fluctuations in the hot gas in the Perseus and Virgo clusters suggest that heating, produced by the dissipation of turbulent gas motions driven by the plasma bubbles as they rise like buoyant balloons, may balance the gas cooling (Zhuravleva *et al.* 2014).

In addition to the feedback commonly observed in present epoch gas rich systems, at early epochs, feedback from the SMBH is now realized to be a key ingredient in galaxy evolution models to produce the correlations between the SMBH mass and galaxy properties (e.g., Ferrarese & Merritt 2000, Gebhardt *et al.* 2000) as well as producing the observed galaxy luminosity function where feedback from SNe is needed to match the faint end of the luminosity function and AGN feedback is needed to match the bright end (e.g., Croton *et al.* 2006, Bower *et al.* 2006).

M87 at the center of the Virgo cluster with a distance of 16 Mpc is ideal for studying the feedback process. In the old parlance, it has a classical cooling flow of about 25 $M_\odot\ yr^{-1}$. However, the galaxy is a typical "red and dead" massive elliptical. The central SMBH is currently active with a moderate radiative luminosity while most of its power is directed through its famous jet which has created a series of buoyant bubbles seen in the radio and X-ray as well as a very clear example of a classic shock (Marshall *et al.* 2002, Owen, Eilek & Kassim 2000, Forman *et al.* 2007). Below we describe a detailed analysis of the 12 Myr old outburst in M87 where the VLA radio observations and Chandra X-ray observations, combined with a shock model, allow us to understand the energy outburst of the SMBH and how energy is partitioned between bubbles and shocks. We also are able to characterize the parameters of the outburst including its energy and duration.

2. M87 - a canonical example of SMBH feedback

M87 hosts a 6×10^9 $M_\odot$ SMBH (Gebhardt *et al.* 2011). The associated jet was discovered almost 100 years ago and is seen over a very broad wavelength range (Curtis 1918, Marshall *et al.* 2002). M87 has undergone a sequence of outbursts including:

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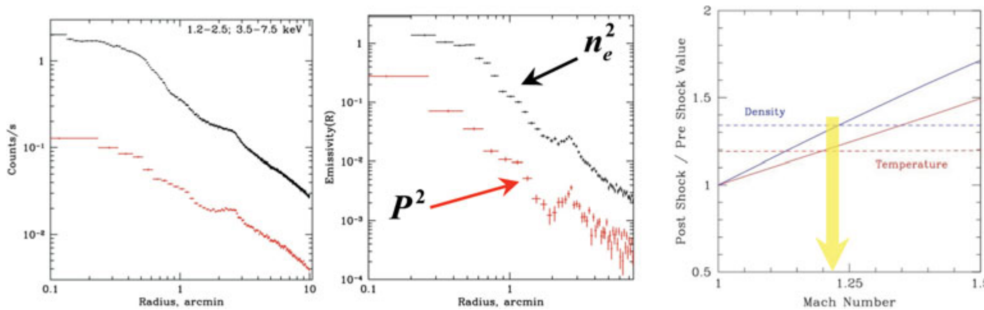

Figure 2. X-ray radial profiles and shock properties of M87. a) Radial surface brightness profiles in two energy bands that are sensitive to density (1.2-2.5 keV, upper curve; 3.5-7.5 keV lower curve); b) Deprojected emissivity in the same two bands as panel a) showing density squared and pressure squared. In both panels, the very pronounced feature at 2.8′ is clearly seen as a perturbation in both density and temperature.; c) the density and temperature shock jump conditions for $\gamma = 5/3$ (upper and lower solid lines, respectively) and the observed density and temperature jumps (dashed upper and lower lines, respectively). The intersections of the observed density and temperature jumps with the jump conditions yield *consistent independent* measurements for the shock Mach number of $M \sim 1.2$.

• the current outburst with its multi-wavelength jet and central cavity (Hines, Owen & Eilek 1989. Owen, Eilek & Kassim 2000, Marshall *et al.* 2002, Forman *et al.* 2007)

• the 13 kpc shock (2.8′) seen as a nearly complete azimuthal ring with an age of $\sim$ 12 Myr (see Fig. 1b).

• the "mushroom cloud" with stem and torus rising to the east (Fig. 1c) with an age of approximately 40 Myrs (the buoyancy time for the eastern torus to rise to its present position at $\sim c_s/2$) along with an opposing, but disrupted, "arm" extending to the south-west. X-rays shows filamentary arms uplifted by the radio torus and filamentary arms associated with the SW radio arm (see Fig. 1a).

• outer "pancakes" (see Fig. 1c) which are probably buoyant bubbles flattened into "pancakes" as the bubbles rose in M87's atmosphere (Churazov *et al.* 2001) with estimated ages of 100-150 Myr (Owen, Eilek & Kassim 2000 but also see de Gasperin *et al.* 2012 who estimate a shorter age of about 40 Myrs).

3. The 12 Myr old outburst and the X-ray shock

As Forman *et al.* (2007) showed, over the temperature range 1-3 keV, the Chandra count rate in the hard X-ray band from 3.5-7.5 keV, is a measure of the integral (projected on the sky) of the square of the pressure. Similarly, the 1.2-2.5 keV band yields the integral (projected on the sky) of the square of the gas density. Hence, for M87, with gas temperatures in the range 1-3 keV, the 3.5 - 7.5 keV image allows us to directly see regions of overpressure. Fig.1b shows the square of the pressure projected on the sky and we see a nearly spherical ring of pressure at 13 kpc radius. The overpressured core which is the "piston" that drove the observed shock and is now being re-inflated by another outburst is clearly seen in Fig. 7b of Forman *et al.* (2007).

Fig. 2 shows the radial profiles in the two energy bands 1.2-2.5 keV and 3.5-7.5 keV which provide measures of gas density and gas pressure, and allow two independent measures of the shock Mach number through the Rankine-Hugoniot shock jump equations. Quantitatively, the Chandra observations yield gas density and gas temperature jumps of $\rho_2/\rho_1 = 1.34$ and $T_2/T_1 = 1.18$. In turn these two *independent* measures of the shock properties yield two Mach numbers derived from the gas temperature and density of

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$M_T = 1.24$ and $M_\rho = 1.18$, respectively and in very good agreement (shown graphically in Fig. 2c). Thus, we have a classical low Mach number shock $M = 1.2$.

By further comparing the size of the driving piston and the observed gas density and gas temperature profiles with a simple shock model (Forman *et al.* 2014), we are able to derive all the parameters of the outburst. We find that the energy of the 12 Myr old outburst is $\sim 5 \times 10^{57}$ ergs (fixed by the Mach number of the $2.8'$ shock) and the outburst duration is about 1-3 Myr. The key to constraining the outburst duration is that a short duration outburst with the same total energy, would produce a low density, high temperature region surrounding the piston which is *not* observed. Instead, the outburst must be of sufficiently long duration to maintain a cool region surrounding the driving piston. The model shows that very roughly, 25% of the outburst energy is carried away by the weak shock, 25% is deposited in the shocked gas, and about 50% of the energy is contained in the inflated bubble (the piston). As Churazov *et al.* (2001) showed, the bubble energy is captured in the cluster core. Most recently, in a study of M87 and Perseus, Zhuravleva et al. (2014) indirectly estimated the spectrum of turbulent motions and showed that turbulent heating is sufficient to offset radiative cooling and indeed appears to balance it locally at each radius. The turbulence is excited by the motions of buoyant relativistic plasma bubbles that are inflated by jets from the SMBH.

In summary, the SMBH energy output matches radiative losses from the core (a few times 10^{43} ergs s^{-1}). The central bubble will rise and lose energy with about $\sim 50\%$ of the total bubble enthalpy transferred to the gas by the time the bubble has risen to a few tens of kpc. The bubble enthalpy is transferred to turbulent gas motions which are now being detected in both M87 and the Perseus cluster (Zhuravleva *et al.* 2014).

The feedback phenomenon outlined for M87 applies to a wide range of systems from optically luminous galaxies through groups to rich clusters. On the smallest mass scales of individual galaxies, a typical example is NGC4636 (Jones *et al.* 2002, Baldi *et al.* 2009) with bubble scales of a few kpc, a total energy of $\sim 10^{56}$ ergs produced by the mechanical power from the SMBH of $\sim 2 \times 10^{42}$ ergs s^{-1}. As we have discussed above, M87, on a scale of 13 kpc, shows an outburst with total energy 5×10^{57} ergs with an average SMBH output power of a few times 10^{43} ergs s^{-1}. On cluster scales of a few hundred kpc, MS0735 shows cavities implying outbursts of $\sim 1.2 \times 10^{62}$ ergs and a power in excess of $\sim 4 \times 10^{46}$ ergs s^{-1}(McNamara *et al.* 2009).

4. Square Meter Arc Second Telescope for X-rays - SMART-X

Recent technological developments support the feasibility of building an X-ray observatory in the 2020s that will have angular resolution comparable to Chandra accompanied by more than an order of magnitude increase in sensitivity in the 0.2-10 keV energy band. This mission concept is called SMART-X, the Square Meter Arcsecond-Resolution Telescope for X-rays (see http://smart-x.cfa.harvard.edu/ for more details). One approach to high angular resolution with light weight mirrors exploits a piezo-electric layer applied to thin glass segments. Building on the International X-ray Observatory mirror technology developments, this added feature, has the potential for achieving a factor of 30 increase in effective area compared to Chandra while maintaining a large field of view with sub-arcsecond imaging (see Vikhlinin *et al.* 2012, Vikhlinin 2013). SMART-X has a 10m focal length with 3m diameter mirrors providing subarcsec ($\sim 0.5''$) angular resolution and operating in the 0.2–10 keV energy band. The telescope concept would have two focal plane instruments and insertable critical-angle transmission gratings with a separate readout detector array.

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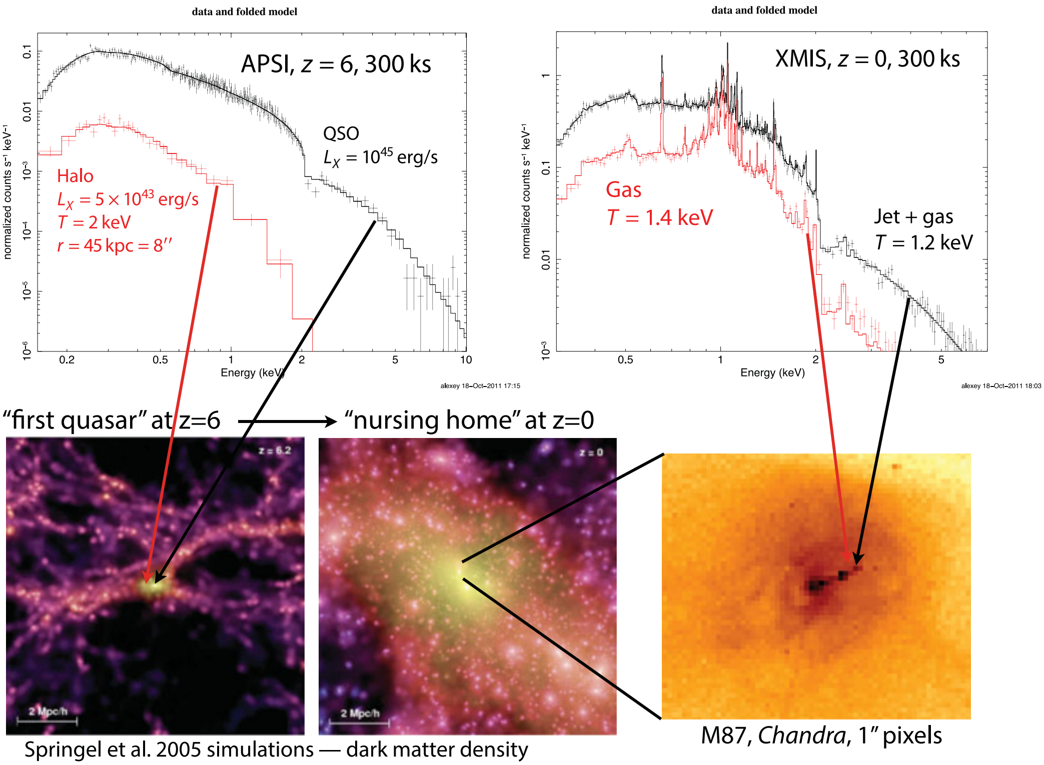

Figure 3. (top left) Simulation of the spectra of a quasar and its host hot gaseous corona at $z \sim 6$ as one would expect for M87 in its youth as observed with a CMOS-like detector in 300 ks with a 2.3 m^2 effective area X-ray telescope having $< 1''$ angular resolution. With high angular resolution, the emission from the luminous AGN can be separated from the emission from the hot corona filling the dark matter halo in which the quasar is embedded. (top right) Simulated spectra of a $1''$ patch of M87 and its jet observed with the same telescope and a microcalorimter array showing the rich gas spectrum and the spectrum of the jet. Lower left panels show the evolution of structure in a dark matter simulation from $z \sim 6$ to the present and the right image shows the core of M87 as observed with Chandra. A $< 1''$ angular resolution telescope with large effective area can study the evolution of systems like M87 from high redshift to the present and observe the transition from the radiative mode to the "radio" mode (where the accretion power is channeled into the mechanical power of the jet).

SMART-X promises a revolution in our ability to probe the evolution of SMBHs and their surrounding environments. Fig. 3 shows the results of a modest 300 ks observation of M87 at the present epoch and its predecessor at $z \sim 6$, more than 12 Gyr earlier, when the SMBH has already grown to $\sim 10^9$ $M_\odot$, but it resides in a much smaller dark matter halo than at present. With sub-arcsecond angular resolution, SMART-X can isolate the hot corona bound in the dark matter halo from the luminous ($\sim 10^{45}$ ergs s^{-1}) AGN, and provide the gas mass, temperature, and abundance of the hot corona. A SMART-X mission could follow the growth of M87-like systems from high redshift to the present. This would yield a unique probe of feedback by AGN over the bulk of the life time of the Universe and allow us to understand the transition between the radiatively efficient accretion mode to the radiatively inefficient mode as the quasar-mode ends and M87-like systems transition to the massive galaxies with large SMBHs that are seen at the present epoch (Churazov *et al.* 2005). Understanding these transitions and effects on the

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surrounding environment is key to understanding the formation of the early-type galaxy population.

In addition to probing high redshifts, a SMART-X mission would enable unprecedented views of structure in the local Universe. Using the high energy resolution microcalorimeter, studies of the hot coronae around galaxies and their jets would provide detailed observations of the feedback at the present epoch that maintains massive galaxies in the "red and dead" population (Fig. 3, right panels).

5. Conclusion

In conclusion, the feedback process observed in detail around M87 is common throughout hot atmospheres from individual early-type galaxies to massive clusters. Deep Chandra observations have allowed us to derive the characteristcs of M87's SMBH outbursts and have shown that these outbursts are of moderate duration (a few Myrs) and that the bulk of the energy is deposited into the buoyant bubbles.

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