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The effects of outbursts from Supermassive Black Holes: A close look at M87

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Abstract. Supermassive black holes (SMBHs) play fundamental roles in the evolution of galaxies, groups, and clusters. The fossil record of supermassive black hole outbursts is seen through the cavities and shocks that are imprinted on these gas-rich systems. For M87, the central galaxy in the Virgo cluster, deep Chandra observations illustrate the physics of AGN feedback in hot, gas-rich atmospheres and allow measurements of the age, duration, and power of the outburst from the supermassive black hole in M87 that produced the observed cavities and shocks in the hot X-ray atmosphere.

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

1. Introduction

With masses that can exceed 10^{15} solar masses, clusters of galaxies are the largest gravitationally bound objects in the Universe. Clusters form at the nodes of the cosmic web, through the infall of groups and small clusters and occasionally through the merger of massive clusters. The gas is clusters is heated primarily by the energy released during their initial gravitational collapse. While some of this gas has cooled to form galaxies, most of the baryons, especially in massive clusters, remain in the form of a hot intracluster gas.

Early X-ray imaging observations from Einstein and ROSAT allowed astronomers to map the density of the hot gas in clusters of galaxies (see review by Forman & Jones 1982). In many clusters, the gas density increases toward the cluster center. Often the gas density in the cluster core is so high that the gas in these regions is cooling rapidly and should accrete onto the cluster centers (see Fabian & Nulsen 1977 and Fabian 1994). However since the predicted large amounts of cool gas in cluster cores were not detected, there was, at that time, a perceived "cooling flow" problem.

Two major X-ray observatories, Chandra and XMM-Newton, both launched 20 years ago, allow astronomers to map the density and temperature of the gas in early type galaxies, groups and clusters. These measurements of the gas density and temperature are then used to map the distribution of the total mass in groups and clusters, which is primarily dark matter. Chandra's arcsecond spatial resolution also has allowed the detection and study of very energetic outbursts from supermassive black holes in the cores of galaxies, groups and clusters (e.g. Churazov *et al.* 2000, 2005; Fabian *et al.* 2003; McNamara *et al.* 2005; Fabian 2012).

A large early-type galaxy lies at the center of nearly all cool-core clusters and groups. At the center of this galaxy is a supermassive black hole (SMBH). At very early epochs, these massive black holes grew rapidly through mass accretion and are observed as very luminous quasars. At the present epoch, the SMBHs in the centers of clusters accrete matter as the hot gas in the cluster cores cools. Unlike quasars, these supermassive black

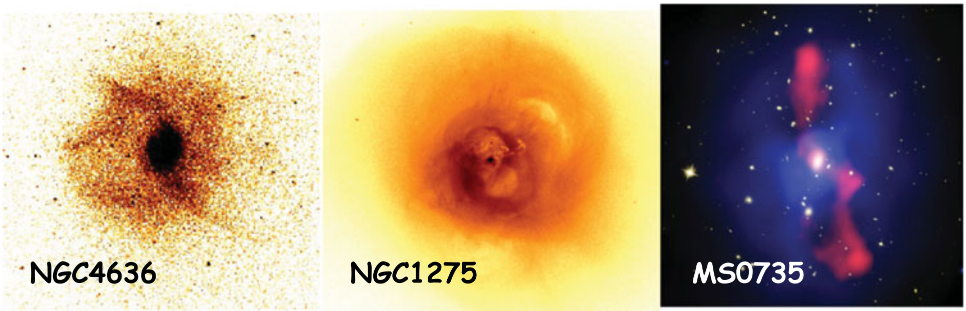

Figure 1. Chandra observations show cavities produced by outbursts of supermassive black holes in the hot gas atmospheres of (left) NGC4636 (adapted from Baldi *et al.* 2009), (center) the Perseus cluster (Fabian *et al.* 2000), and (right) MSO735+74 (McNamara *et al.* 2009).

holes are generally radiatively faint and are in a state of "maintenance feedback," in which the SMBHs, although accreting at levels well below the Eddington mass accretion rate, can undergo AGN outbursts which create cavities in the hot gas halos of early type galaxies and clusters (see Figure 1). By measuring the volumes of these cavities, observers have calculated the energy required to displace the hot gas and have determined that the kinetic energies of the local SMBHs are far larger than their radiative energies.

For M87, with a SMBH mass of 3-6 $\times 10^9 M_{sun}$ (Harms *et al.* 1994; Ford *et al.* 1994; Gebhardt *et al.* 2011; Walsh *et al.* 2013), the Eddington luminosity of M87's SMBH is 4-8 $\times 10^{47}$ ergs s^{-1}. However the current observed bolometric luminosity is only 3×10^{42} ergs s^{-1}, five orders of magnitude lower than the expected Eddington luminosity. In addition the estimated jet mechanical power is significantly higher, $\approx 10^{44}$ ergs s^{-1}(e.g. Owen, Eilek & Kassim 2000; Stawarz *et al.* 2006). This conclusion is supported M87's spectral energy distribution (e.g. Reynolds *et al.* 1996; Yuan *et al.* 2009; Mościbrodzka *et al.* 2016). Together, these properties of M87's SMBH suggest M87 has a hot, radiatively inefficient accretion flow (e.g. Yuan & Narayan 2014).

Outbursts from a central SMBH can reheat much of the radiatively cooling gas in the cores of elliptical galaxies, groups, and clusters and thus prevent new stars from forming in the cores. This process leads to the separation of the red elliptical galaxies, which are massive and reside in dense, gas rich environments, from the generally lower mass spiral galaxies, which lie in the field or in poor galaxy groups that have little or no hot intracluster gas. However, there are a small number of clusters that have relatively cool gas in their cores and intense star formation in their central galaxy. A primary example is the Phoenix Cluster where the high level of star formation in the core is produced by a "runaway" cooling flow (McDonald *et al.* 2012, 2015).

The family of systems with hot diffuse gas and cavities produced by outbursts from their central supermassive black hole is illustrated in Figure 1. These systems range from relatively isolated elliptical and S0 galaxies (e.g. NGC4636; Jones *et al.* 2002; Baldi *et al.* 2009) with relatively low X-ray luminosities, cool gas temperatures ($\sim 10^7$ K) and a low fraction of gas mass to stellar mass, to galaxy groups and finally to the massive clusters. Examples of massive clusters include Perseus (Fabian *et al.* 2000) and MSO735+74 (McNamara *et al.* 2005), that have X-ray luminosities up to several 10^{45} ergs s^{-1}, high gas temperatures (10^8 K) and seven to ten times the mass in hot gas compared to the mass in all the cluster galaxies. Although in clusters, the hot X-ray emitting gas dominates the stellar mass, the hot gas is only about 15% of the total cluster mass. Most of the matter in clusters is Dark Matter.

Figure 2 shows the ROSAT map of the X-ray emission from the Virgo cluster (Böhringer *et al.* 1994). The ROSAT X-ray image clearly shows that M87 is the central

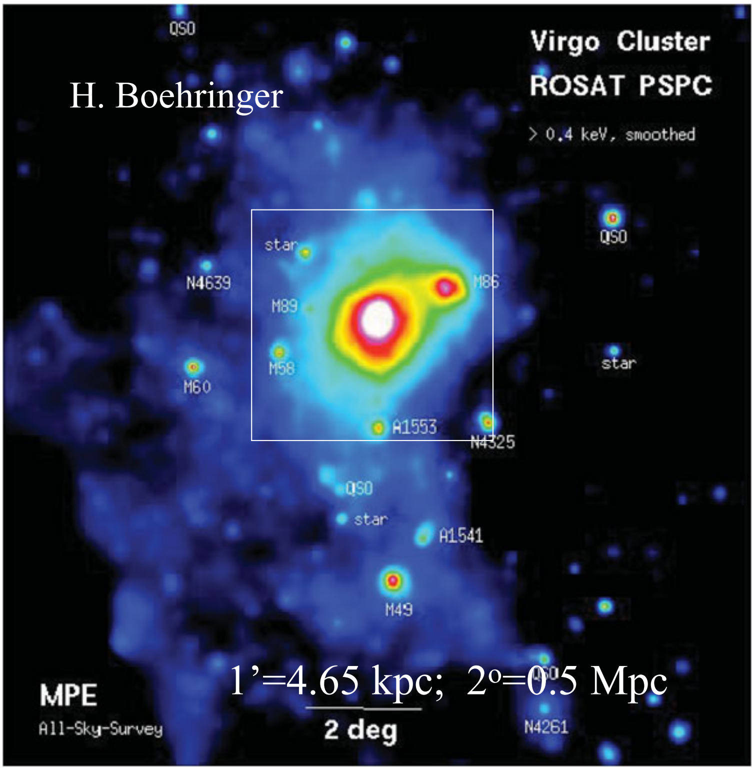

Figure 2. The X-ray emission of the Virgo Cluster as mapped by ROSAT (Böhringer *et al.* 1994) shows the brightest X-ray emission centered on M87, with other bright regions of extended X-ray emission associated with the elliptical galaxies M86, M49 and M60.

dominant galaxy in the Virgo Cluster, even though M49 (NGC4472) is optically slightly more luminous than M87. M87 also hosts a supermassive black hole in its core, which was observed in April 2017 with the Event Horizon Telescope (Event Horizon Telescope Collaboration *et al.* 2019), as well as a classic cooling flow. These characteristics, as well as the proximity of the Virgo cluster, make M87 an ideal system to study the interaction of the SMBH and the hot gas. A detailed analysis of the M87 jet was carried out by Marshall *et al.* (2002), while the comprehensive analysis of the AGN outburst published by Forman *et al.* (2017) forms the basis of this review.

2. SMBH feedback in M87

While we now know that feedback from supermassive black holes is key to understanding how galaxies evolve (see review by McNamara & Nulsen 2007), we still do not know exactly how this feedback works. In Figure 3, Chandra images of M87 in the "soft" (0.2-2.0 keV) energy band (left panel) and in the "hard" (2.0-3.5 keV) energy band (middle panel), along with the optical image of M87 (right panel) are all shown on the same physical scale. The "soft" band image shows the X-ray bright core and two long X-ray filaments of cool gas. The "hard" band image shows the bright central core of the cluster and the hot gas that was shock heated by the AGN outburst that occurred about 13 million years ago.

Figure 4 shows many possible feedback paths for a massive galaxy in a hot gaseous atmosphere with a supermassive black hole in its core. Although the correct evolutionary path is not yet known, what is currently agreed, is that the mechanical input, as seen

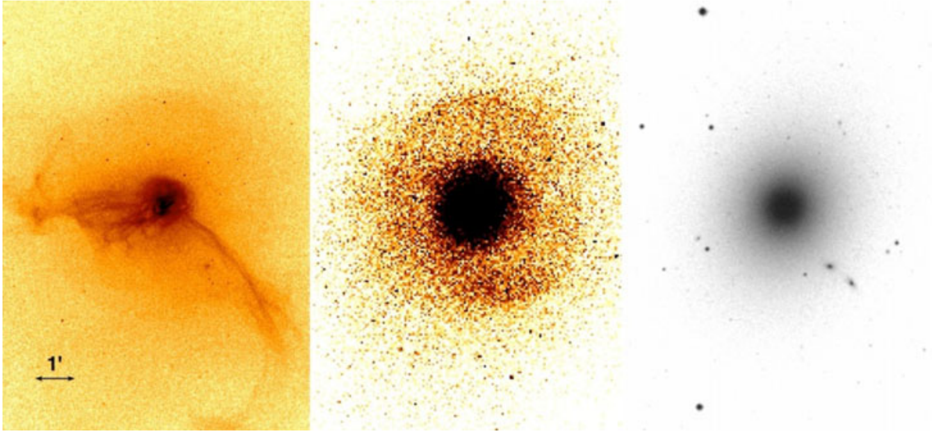

Figure 3. Chandra images of M87 in the “soft” (0.2-2.0 keV) energy band (left image) and “hard” (2.0-3.5 keV) energy band (center image), and the optical image of the galaxy (right image). All three images are on the same physical scale and for the same region of the sky. At the distance of M87, 1′ is ∼5 kpc. The soft band shows long extended filaments of cool gas, while the hard band image clearly shows the location of the shock from the AGN outburst.

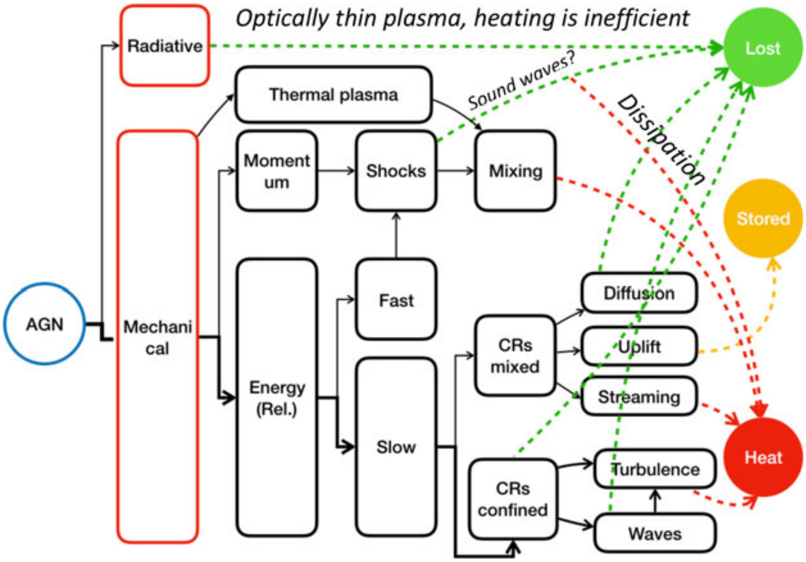

Figure 4. The process of gas cooling onto a supermassive black hole and generating outbursts can follow many possible paths, as illustrated by this figure that was adapted from an earlier version made by Eugene Churazov.

through the inflation of bubbles and occasionally the presence of shocks in the gas, in crucial to reheating the cooling gas, while nearly all of the radiative energy from the AGN is lost from the system. One possible “path” to reheating relies on turbulence generated by the rising buoyant bubbles (see Churazov *et al.* 2001 and Zhuravleva *et al.* 2014). While the exact path that the mechanical energy takes is still unclear, the deep Chandra observations of M87 provide important constraints on both the duration of the AGN outburst and the heating of the intracluster gas (Forman *et al.* 2017).

At the present epoch, the mechanical power of supermassive black holes dominates the radiated power in clusters, groups and gas-rich early type galaxies. As described below,

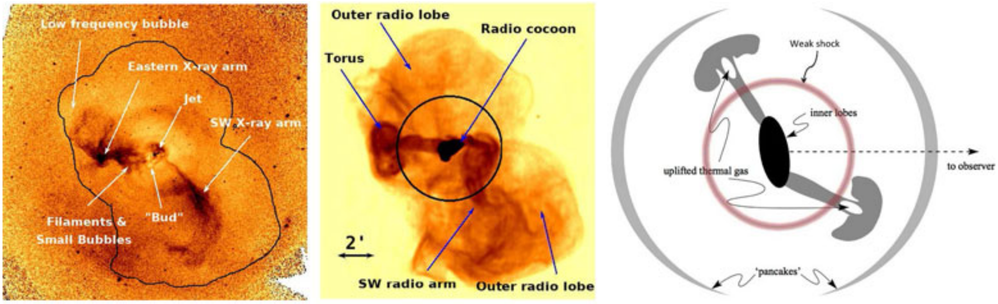

Figure 5. The left panel shows the Chandra X-ray image of M87, divided by the average X-ray radial profile to better highlight the faint X-ray structures, particularly the "arms", jet, and small bubbles. The black outline of the radio emission derived from the 90 cm VLA observation shown in the center panel (adapted from Owen, Eilek & Kassim 2000), is superposed on the X-ray image in the left panel. The right panel shows a schematic of the M87 system with the inner radio lobes, the "arms" of uplifted thermal gas, the shock shown in red, and the outer radio lobes, which are labeled as "pancakes".

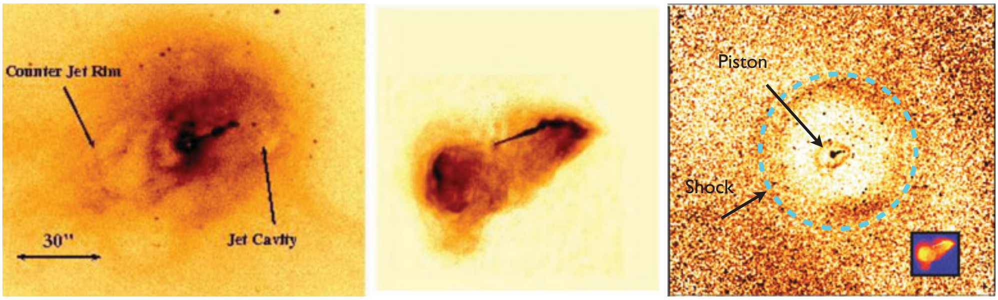

Figure 6. The left panel shows the Chandra image of the core of M87 with cavities in the hot gas and surrounding filaments created by outbursts from the supermassive black hole. The central panel shows the radio jet and radio lobes in the core of M87. The right panel shows the result of dividing the counts in the X-ray image by the average radial surface brightness profile, which "flattens" the field and enhances the features in the core, in particular the emission from the X-ray jet, as well as the hot X-ray emitting inner rim, labeled here as the "piston". The X-ray enhancement at the shock, produced by the AGN outburst, is marked by the blue dotted circle and is clearly visible.

the X-ray and radio observations of M87 together can chronicle the history of AGN outbursts from the supermassive blackhole over the past 150 Myr. The left and center images in Figure 5 show the Chandra X-ray and radio images of M87.

In the left image in Figure 5, the faint X-ray structures in M87 have been highlighted, compared to what can be seen in the original deep Chandra observation, by dividing the background subtracted image by the average X-ray radial surface brightness. This image clearly shows the X-ray "arms" and small bubbles, as well as the X-ray jet which extends $20''$ to the northwest.

The M87 jet has filled the central cavity with relativistic plasma that is seen in the JVLA radio image (Owen, Eilek & Kassim 2000), in the central panels of Figures 5 and 6. The outline of the JVLA extended radio emission is shown superposed on the Chandra image in the left panel of Figure 5. The two large, outer radio lobes northeast and southwest of the M87 nucleus have ages of $\approx$100$-$150 million years. Thus these observations provide evidence for an outburst from the SMBH about 150 million years ago. A filamentary radio arm, extending southwest of the nucleus, also can be seen in the

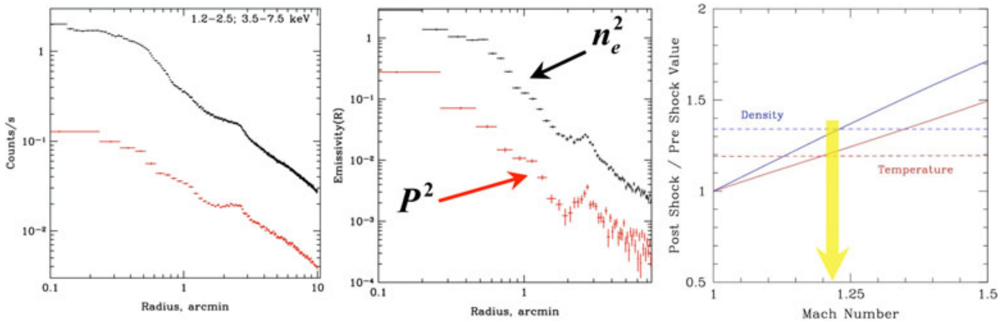

Figure 7. The left panel shows the radial surface brightness profile in the energy band 1.2-2.5 keV (in black) and in the hard energy band 3.5-7.5 keV (in red), extracted from a 90 degree azimuth centered on north, with point sources removed and corrected for telescope vignetting and exposure time. The "bumps" at a radius of 2.7′ (13 kpc, at the distance of M87), in both the surface brightness profiles (left panel) and in the plots of the square of the density and pressure (central panel), are the strongest features in the X-ray surface brightness profiles. These bumps correspond to the shock at a radius of 13 kpc produced by an outburst from the SMBH that occurred about 12 Myr ago. The current outburst is now re-inflating the central cavity. The right panel shows the measured ratios of the post shock to pre-shock values of both the gas density and temperature correspond to a Mach number of 1.2.

central panel of Figure 5. These radio features result from an outburst of the SMBH about 70 million years after the outburst that produced the outer radio lobes (Owen, Eilek & Kassim 2000). In addition, the central panel of Figure 5 shows a radio torus (resembling a "mushroom cloud"), to the east of M87, which has risen about 20 kpc from the core, in the last 40 to 70 million years (Owen, Eilek & Kassim 2000; Churazov *et al.* 2001).

A comparison of the Chandra and radio observations (Figures 5 and 6) shows X-ray filaments that are coincident with the radio structures. While Figure 5 shows the structures on the larger scales, Figure 6 shows the the detailed structure in the core seen in the deep Chandra observations (left panel) and in the deep radio observations (middle panel). Also a bubble (labeled as "bud" in Figure 5 and shown on a larger scale in Figure 6) that is now separating from the central cocoon as seen in both the X-ray and radio images, while filamentary X-ray structures, extending to the east of the nucleus, are likely the remnants of small bubbles produced by less energetic nuclear outbursts. The X-ray emitting gas in the X-ray arms is cooler than the gas in the outer regions, thus supporting the idea that the X-ray arms are uplifted from the core by rising bubbles created in an outburst by the SMBH. While the shock from the AGN outburst is clearly visible in the Chandra "hard" band image (3.5 to 7 keV), as shown in the central image of Figure 5, the largest bubbles seen in the radio observation are not apparent in the X-ray images of the hot gas.

The left panel in Figure 7 shows the radial surface brightness profile in the soft energy band (1.2-2.5 keV) in black and in the hard energy band (3.5-7.5 keV) in red (for additional details, see the caption for Figure 7). The center panel shows the radial profiles of the square of the gas density and the square of the gas pressure. "Bumps" in both profiles, at a radius of 2.7′ (13 kpc, at the distance of M87) are the strongest features seen in the four profiles and show the existence of a shock at a radius of 13 kpc that was produced by the current outburst from the M87 SMBH that is now re-inflating the central X-ray cavity. The right panel in Figure 7 shows that the measured ratios of the post-shock to pre-shock values for both the gas density and temperature correspond to a Mach number of 1.2 for the shock that produced the features at a radius of 13 kpc.

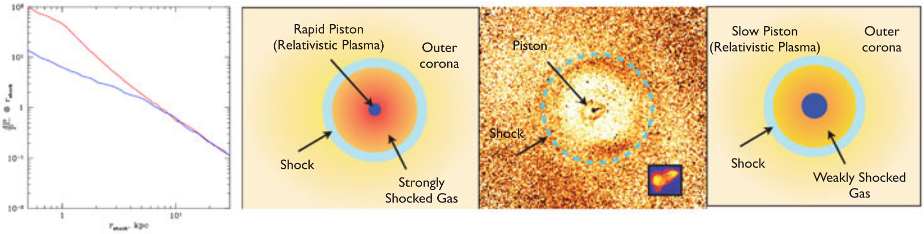

Figure 8. The left panel shows the evolution of the shock strength, parameterized as the pressure jump for a short (0.6 million year) duration outburst in blue, compared to a long duration outburst (2.2 million years) in red, extracted from a 90 degree azimuth centered on north, with point sources removed and corrected for telescope vignetting and exposure. In the second panel, the skematic drawing illustrates the strongly shocked gas in the galaxy halo that would result from a short intense SMBH outburst, compared the weakly shocked gas in the galaxy halo that would result from a "slow piston," illustrated in the fourth panel.

A total of four outbursts from the supermassive black hole in M87 have been identified, with ages up to ≈150 million years, with the most recent outburst still ongoing. The plasma bubbles in the outer region of M87 are buoyant and rise in the hot atmosphere at about 300 km s^{-1}. These bubbles uplift the cool gas from the core, resulting in the formation of the cool X-ray arms shown in the first panel of Figure 5. In addition to these four AGN outbursts, there may be even older outbursts from the SMBH, with the outer radio bubbles being the repository of the energy from these past outbursts.

The fate of the energy released from a SMBH outburst is gas motion. The rising bubble created by the outburst forms a torus. The plot in Figure 8 shows how much bubble enthalpy remains as a function of distance from the SMBH. By the time the bubble is 10 kpc from the SMBH, it has lost about half its enthalpy, which has gone into gas mostions and ultimately into heating the gas. This "solves" what was called "the cluster cooling flow problem." In Virgo and most cool core clusters, the cooling gas is reheated by outbursts from the central SMBH (see Zhuravleva *et al.* 2014).

The left panel in Figure 8 shows the evolution of the shock strength, parameterized as the pressure jump for a short (0.6 million year) duration outburst from the SMBH in blue, compared to a long duration outburst (2.2 million years) in red. Although the two curves differ dramatically in the core of M87, they both match the observed shock at a radius of 13 kpc.

The two senarios for the SMBH outburst in M87, in particular a short (0.6 million year) outburst verses a long (2.2 million year) outburst, are shown in the second and fourth panels of Figure 8. The second panel illustrates the case of a short duration (10^5 years), powerful outburst, with a strong shock that would be driven into the surrounding hot atmosphere. In this scenario, at the present time, the region interior to the shock would be hot. The fourth panel of Figure 8 shows the case of a longer duration (2.2×10^6 years) and thus more "gentle" outburst that would still generate the same magnitude shock at 13 kpc as that of the short duration outburst. However in this case, the gas interior to the shock would be only weakly shocked and the central plasma-filled piston would be larger, than in the case of a short duration outburst. The third panel shows the observed X-ray emission from the core of M87. In this image, the X-ray emission has been "flattened" by dividing the observed emission by the smoothed radial profile. This analysis of the image highlights the central ring of X-ray emission (labeled as "piston") as well as the increased X-ray emission at the shock.

In summary, a total of four outbursts from the supermassive black hole in M87 have been identified, with ages up to ≈150 million years, with the most recent outburst still ongoing. The plasma bubbles in the outer region of M87 are buoyant and rise in the hot atmosphere at about 300 km s^{-1}. These bubbles gently uplift the cool gas from the core, resulting in the formation of the cool X-ray arms shown in the first panel of Figure 5. In addition to these four AGN outbursts, there may be even older outbursts from the SMBH, with the outer radio bubbles being the repository of these past outbursts.

Thus, for the first time, from the analysis of X-ray and radio observations presented here, we can understand in considerable detail the history of the AGN outbursts that occurred in the core of M87 over the last ≈150 million years. The supermassive black hole in M87 has had at least four outbursts. M87 hosts old radio bubbles, produced 100-150 million years ago, as well as the radio torus and arms and the X-ray arms, which were produced by an AGN outburst about 40 Myrs ago. In addition the hard X-ray image shows a shock in the hot gas, which resulted from the AGN outburst that occurred 12 million years ago. This relatively recent AGN outburst also created the central small X-ray cavity in the core. Finally, there is evidence that the jet is now reinflating the central cavity that drove the main shock that is observed at a radius of 13 kpc. Thus, in total, the supermassive black hole in M87 has had at least four outbursts in the past ≈150 million years, and maybe many more older outbursts, with the outer bubbles being the repository of the energy from these past outbursts. In addition to understanding the history of outbursts from the SMBH in M87, from the Chandra observations of M87, we also understand that the absence of a strongly shock-heated region exterior to the central cavity implies a “gentle”, relatively long outburst (see Forman *et al.* 2017 for details). Quantitatively, the size of the cavity and the shock strength constrain the outburst duration to be about 2 Myr.

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