SHOCKS, BUBBLES, AND FILAMENTS: THE EFFECTS OF SUPERMASSIVE BLACK HOLE OUTBURSTS

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ABSTRACT

We summarize the results derived from a 500 ksec Chandra observation of M87. At hard energies (3.5-7.5 keV), we detect a nearly circular shell of outer radius $2.8'$ (13 kpc). This ring of hard X-ray emission provides a clear signature of a weak shock, driven by an outburst from the supermassive black hole at the center of M87. We find that the observed density and temperature jumps are consistent with a Mach $M \sim 1.2$ shock (for monoatomic gas with $\gamma = 5/3$). From a series of models, we find that the outburst energy required to drive the shock is 5×10^{57} ergs and that the outburst occurred $\sim 14 \times 10^6$ years ago. At soft energies (0.5-1.0 keV), we detect a complex filamentary web. This filamentary structure is particularly striking in the eastern arm where we suggest the filaments are the outer edges of a series of buoyant bubbles filled with relativistic plasma, produced by the central supermassive black hole, in a succession of small outbursts.

The M87 outburst is intermediate in energy and radial scale between outbursts from supermassive black holes in "normal" galaxies with typical outbursts of $\sim 10^{57}$ ergs and several spectacular outbursts detected from central galaxies in rich clusters with outburst energies up to 10^{62} ergs. Over a wide range, active nuclei are able to provide significant energy to the radiatively cooling gas in galaxy, group, and cluster atmospheres.

Key words: Galaxy; X-ray ; M87.

1. INTRODUCTION

M87, in the core of the nearby Virgo cluster, is typical of many collapsed dark matter halos at whose centers lies a dominant early type galaxy. These galaxies are surrounded by a hot, thermal, X-ray emitting plasma which is generally gravitationally bound in the dark matter halo. The dark matter halos, spanning a range of masses and hence virialized plasma temperatures, include individual early type galaxies (with gas temperatures of $kT \sim 0.5 - 1.0$ keV) through groups ($kT \sim 1 - 3$keV) to rich clusters ($kT \sim 3 - 10$keV). Typically the hot plasma is peaked on the dominant galaxy and has a high central gas density and thus a short cooling time. A simple "cooling flow" model for this thermal plasma (e.g., [6, 3]) predicts mass deposition rates as high as 1000 $M_\odot$ yr^{-1} (e.g., [5]). However, observations with XMM-Newton have shown that mass deposition rates in cooling flow clusters are at least five times smaller than expected in the standard model ([19] and references therein). This dramatic reduction in the amount of cool gas requires considerable energy input to compensate for radiative losses. In this contribution, we discuss energy input from the central supermassive black hole (SMBH) with a focus on M87 and its surrounding hot atmosphere.

2. M87'S CLASSICAL SHOCK

M87, a massive elliptical galaxy at the center of the Virgo cluster, hosts a 3×10^9 $M_\odot$black hole [14] with a $20''$ long jet [1] seen at radio, optical, and X-ray wavelengths [15, 12] and references therein. Its surrounding atmosphere has a gas temperature of about 2 keV and the classical "cooling flow" model predicts a mass deposition rate of $\sim 20 M_\odot$ yr^{-1}..

As we discuss below, the supermassive black hole in M87 undergoes outbursts which can replace the energy radiated by the hot atmosphere. The outbursts inflate radio-emitting bubbles of relativistic plasma which drive mild shocks into the surrounding atmosphere and, as these bubbles rise buoyantly in the atmosphere, provide energy to the radiating plasma.[2]

Many of the features seen in M87, were first noted in detailed studies of the Perseus cluster and its central galaxy NGC1275. In the hot atmosphere surrounding NGC1275, a series of weak shocks have been have detected[8]. These weak shocks, if there is sufficient viscosity, can provide sufficient energy to maintain the thermal energy of the gas in the cooling core of the Perseus cluster (see detailed studies including [8, 7]).

[1] At a distance of 16 Mpc, $1' = 4.65$kpc

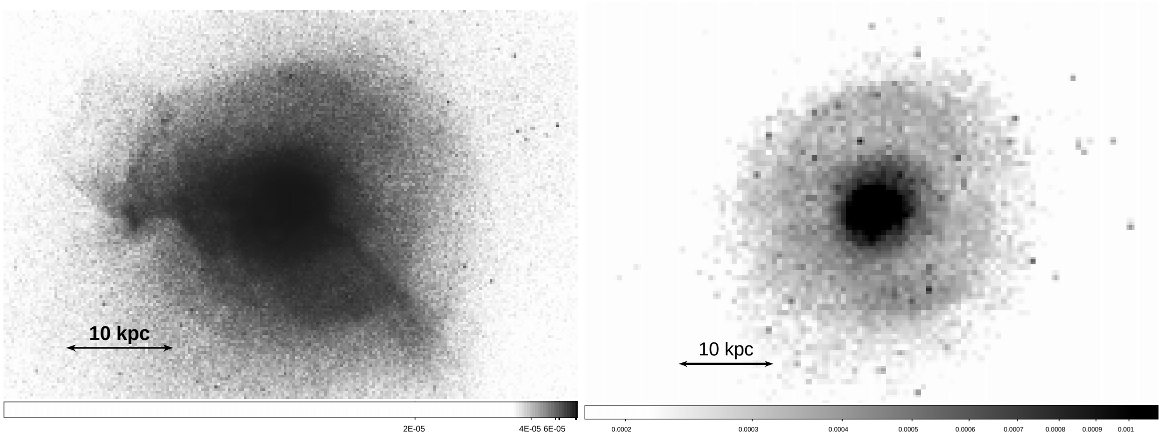

Figure 1. a - The 1.2-2.5 keV band image of M87. Over this energy band, the emission, observed with Chandra, is relatively insensitive to gas temperatures above 1.0 keV. Therefore, this image is a projected map of n^2. b) The 3.5-7.5 keV band image. Over this range, the observed Chandra counts can be shown to depend on P^2, where P is the pressure (see text). Hence, we are directly seeing the nearly circular, overpressured shock.

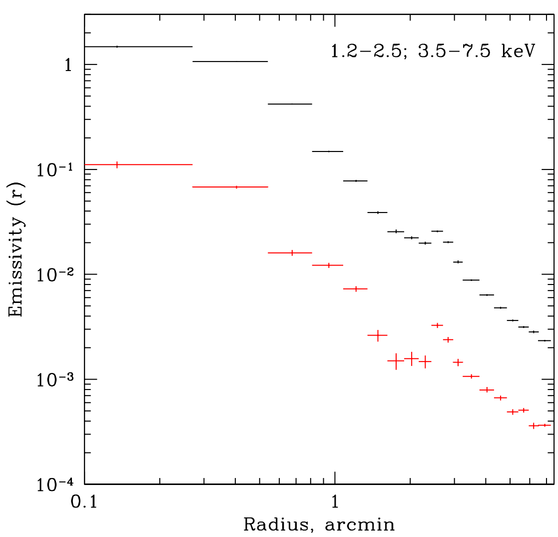

Figure 2. The 1.2-2.5 keV (upper curve) and 3.5-7.5 keV (lower curve) band deprojected emissivity profiles. The shock at $2.8'$ is visible in both energy bands, but most pronounced in the harder energy band, as expected.

3. DEEP CHANDRA IMAGES OF M87

Fig. 1 shows two images of M87 in the 1.2-2.5 keV and 3.5-7.5 keV energy bands. In the 1.2-2.5 keV band, the Chandra count rate depends very weakly on the gas temperature. The observed flux. F, can be expressed as:

$$F \propto n^2\epsilon(T) \propto (P/T)^2\epsilon(T) \propto (P^2\epsilon(T)/T^2) \qquad (1)$$

In the hard energy band, 3.5-7.5 keV, the term $\epsilon(T)/T^2$ depends weakly on T in the energy range 1-4 keV, and hence, the 3.5-7.5 keV band image is approximately an image of the square of the pressure (projected along the line of sight), i.e., $F \propto P^2$. Thus, Fig. 1a shows approximately the square of the projected gas density and Fig. 1b, the square of the projected gas pressure.

The two figures, Fig.1a and b show remarkably different views of M87. In Fig.1a, we see the bright (overexposed) core region harboring the bright nucleus and the jet as well as arms of thermal plasma (see [1, 17, 10] for temperature maps of the arms) extending to the east and southwest as well as a hint of a circular structure at a radius of about 13kpc (see [20, 10, 11] for more details). Fig. 1b shows a totally different picture. Instead of the cool filamentary arms, we see a nearly circular ring of emission. Since this is the "pressure" image, we are viewing a pressure enhancement, a shock. Its existence is clear from the images alone.

4. M87'S CLASSICAL SHOCK

To derive quantitative measurements, we extracted the radial the surface brightness distribution in two energy bands, Fig. 2, to estimate the gas temperature and gas density profiles. In addition, we convert the projected profiles to 3-dimensional distributions. The shock is most clearly visible in the hard energy profile.

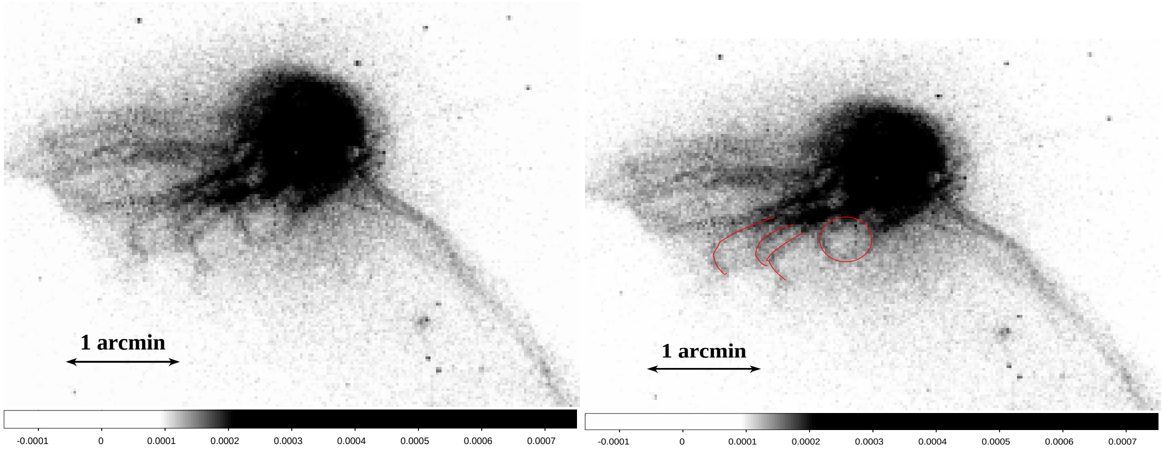

Figure 3. a) The 0.5-1.0 keV band image ($1''$ pixels) showing the web of filaments. The southwestern arm appears as a single long filament while the eastern arm, coincident with the radio "mushroom" stem and cap (see [18, 2] appears as a complex of filaments. b) Same as a) but outlining the innermost "bud", a buoyant bubble with an age of about 10^7 years that coincides with radio emission seen at 6 cm.[13] A sequence of possible bubbles, all older than the bud are also marked. The long filaments composing the eastern arm could be a still older series of smaller bubbles drawn up as the large buoyant bubble seen as the radio cap rose in M87's atmosphere.

The radial profiles of gas temperature and gas density yield values of the temperature and density jumps associated with the shock seen at $2.8'$ (13 kpc). The two jumps yield independent measures of the shock strength using the Rankine-Hugoniot shock jump conditions. The values are in good agreement and are consistent with a weak shock of Mach number $M \sim 1.2$.

We have modelled this shock using a one-dimensional numerical model and are able to derive accurate estimates for the parameters of the shock. In particular, the size of the radio cavity, the piston driving te shock. the present radius of the shock, and the magnitude of the density and temperature discontinuities at the shock, yield an outburst energy of $\sim 5 \times 10^{57}$ ergs and and age of 14×10^6 years.

In addition, we note that M87 appears to be starting another episode of activity with the current jet power at about 10^{44} ergs s^{-1}. Thus, if the current age of the shock represents the typical time between outbursts, then the average power produced by the SMBH is $\sim 10^{43}$ ergs s^{-1}, comparable to the energy radiated from the cooling core and sufficient to balance the cooling of the gas.

We note that the above scenario is rather simple and has relied on 1-d models. The actual situation is undoubtedly more complex. Measurements of the velocity of jet knots argue for a jet that is inclined by about 30° from the line of sight. Hence, the central core, although appearing quite azimuthally symmetric, is quite elongated. Hence, more detailed models should be developed.

5. BUOYANT BUBBLES - LARGE AND SMALL

In addition to the shock and the central cocoon of relativistic plasma, M87 hosts a series of buoyant bubbles (see [18, 2, 10, 11] for details and images of the features discussed). The oldest bubble system, seen as two large low surface brightness, nearly circular radio features, have ages of roughly 10^8 years. The next oldest system is that associated with the eastern arm seen most clearly in the radio and X-ray. The X-ray images show a cool column of thermal plasma, uplifted by the buoyant radio emitting plasma which appears as a torus with a trailing column of plasma. [2, 1, 17, 10, 11]

The new 500 ksec Chandra observation shows that the eastern arm, coincident with the radio column appears as a series of narrow filaments (see Fig. 3). In addition, to the south of these long filaments, we see what may be a series of small ($\sim$ 1kpc) bubbles surrounded by cool filaments. The youngest of these is the "bud" (see Fig.3 and [10, 11] for details) which emanates from the radio coccoon to the southeast.

Thus, in addition to the central cavity and its associated shock, M87 shows a rich series of buoyant bubbles with ages extending over 10^8 yrs.

6. CONCLUSION

The buoyant bubbles and shocks seen in Perseus and M87 which arise from SMBH outbursts, are seen in a wide range of systems whose gaseous atmospheres provide a record of past activity. On the smallest scales of individual galaxies, NGC4636 shows a shock of radius 5 kpc, age 3 Myr, and total energy of 6×10^{56} ergs.[9] On the largest scales, Hydra A, a hot, luminous cluster, shows evidence for a shock with radius 160 kpc, an age of 60 Myr, and a total outburst energy of $\times 10^{61}$ ergs. [16]

SMBH's in luminous early type galaxies are providing significant energy input to their surroundings and appear capable of replacing radiative losses in all systems with hot plasma atmospheres ranging from early type galaxies to rich clusters.[4]

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REFERENCES

[1] Belsole, E. et al. 2001, A&A, 365, L188

[2] Churazov, E., Bruggen, M., Kaiser, C., Böhringer, H. & Forman, W. 2001, ApJ, 554, 261

[3] Cowie, L. & Binney, J. 1977, ApJ, 215, 723

[4] Dunn, R. & Fabian, A. 206, MNRAS in press, astro-ph/0609537

[5] Edge, A. et al. 1994, MNRAS, 270, L1

[6] Fabian, A. & Nulsen, P. 1977, MNRAS, 180, 479

[7] Fabian, A. , Sanders, J. S., Taylor, G. B., Allen, S. W., Crawford, C. S.; Johnstone,, R. M., Iwasawa, K. 2006, MNRAS, 366, 471

[8] Fabian, A. et al. 2003, MNRAS, 334, L43

[9] Finoguenov, A. & Jones, C. 2002, ApJ, 574, 754

[10] Forman, W. et al. 2005, ApJ, 635, 894

[11] Forman, W. et al. 2004, submitted to ApJ, astro-ph/0312576

[12] Harris, D. 2003, NewAR, 47, 617

[13] Hines, D., Owen, F. & Eilek, J. 1989, ApJ, 347, 713

[14] Macchetto, F., Marconi, A., Axon, D. J., Capetti, A., Sparks, W., & Crane, P. 1997, ApJ, 489, 579

[15] Marshall, H., Miller, B., Davis, D., Perlman, E., Wise, M., Canizares, C., Harris, D. 2002, ApJ, 564, 683

[16] Nulsen, P., McNamara, B., Wise, M., David. L. 2005, ApJ, 628, 629

[17] Molendi, S. 2002, ApJ, 580, 815

[18] Owen, F., Eilek, J. & Kassim, N. 2000, ApJ, 543, 611

[19] Peterson, J. et al. 2003, Proceedings of "The Riddle of Cooling Flows in Clusters of Galaxies" eds. Reiprich, Kempner, Soker, astro-ph/0310008

[20] Young, A., Wilson, A., Mundell, C. 2002, ApJ, 579, 560