IN-DEPTH CHANDRA STUDY OF THE AGN FEEDBACK IN VIRGO ELLIPTICAL GALAXY M84

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ABSTRACT

Using deep Chandra observations of M84, we study the energetics of the interaction between the black hole and the interstellar medium of this early-type galaxy. We perform a detailed two-dimensional reconstruction of the properties of the X-ray-emitting gas using a constrained Voronoi tessellation method, identifying the mean trends and carrying out the fluctuation analysis of the thermodynamical properties of the hot ISM. In addition to the PV work associated with the bubble expansion, we identify and measure the wave energy associated with the mildly supersonic bubble expansion. We show that, depending on the age of the cavity and the associated wave, the waves can make a substantial contribution to the total energy release from the AGN. The energy dissipated in the waves tends to be concentrated near the center of M84 and in the direction perpendicular to the bubble outflow, possibly due to the interference of the waves generated by the expansion of northern and southern bubbles. We also find direct evidence for the escape of radio plasma from the ISM of the host galaxy into the intergalactic medium.

Subject headings: intergalactic medium — galaxies: elliptical and lenticular, cD — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

Detailed investigations of the balance between the heating and cooling of the hot interstellar medium (ISM) and intracluster medium (ICM) have been made possible through key observations made by Chandra and XMM-Newton and successes in numerical modeling (see McNamara & Nulsen 2007 for a review). The commonly accepted paradigm states that the feedback mechanism should be ultimately linked to the activity of the supermassive black holes located at the bottom of the potential wells in systems with cool cores.

A standard way of estimating the energy released by an active galactic nucleus (AGN) is to measure the PV work associated with X-ray cavities (bubbles) inflated by the AGN. This is an indirect measurement, as the bubbles are typically observed as depressions in X-ray emissivity. However, the task of estimating the AGN energy injected into the ICM can be accomplished by assuming that such X-ray cavities are in pressure balance with the ICM. One can then infer the total energy contained in the cavities that is available for doing mechanical work (i.e., enthalpy) from \( H = \frac{\gamma}{\gamma - 1} PV \), where \( \gamma \) is the adiabatic index, \( P \) is the pressure, and \( V \) is the bubble volume. Such an observational estimate is further complicated by the fact that the effective adiabatic index \( \gamma \) of the material inside the bubbles is not known. That is, it is not known if the bubbles are predominantly thermal, in which case \( \gamma = 5/3 \) (e.g., Mazzotta et al. 2002 shows that both the thermal and nonthermal models fit the data in the case of the MKW 3 galaxy cluster) or nonthermal, in which case \( \gamma = 4/3 \) (e.g., Sanders & Fabian 2007 in the case of the Perseus cluster). The content of radio lobes and X-ray cavities may depend on such factors as the initial jet composition (\( e^+e^- \) or \( pe^- \)), the efficacy of entrainment of colder thermal ICM gas, or the magnetic pressure support inside the bubbles (Dunn et al. 2006, and references therein). Furthermore, the energy content obtained this way may be a lower limit to the actual total energy released by the AGN if the pressure balance assumption does not hold. An extreme example of this effect is seen in the simulations of very high Mach number jets interacting with the ICM (Binney et al. 2007).

Moreover, X-ray observations show that the standard method for inferring AGN energies leads to the bubble energy increasing in the statistical sense with the distance from the center of the gravitational potential (Diehl et al. 2008). This apparently counterintuitive result may be the result of the erroneous assumption that the bubbles are “born” in pressure equilibrium with the surrounding ICM or ISM.

If the bubbles are overpressured with respect to the ISM, then one would need the internal bubble pressure to correctly estimate the energy inside the bubble. Moreover, if they were overpressured in the past, then this overpressure should have created waves that should have carried some portion of the energy away from the cavities. The standard method of estimating the AGN energy based on the pressure balance and cavity size does not include such contributions to the total energy balance. In addition to increasing the overall energy budget, such waves provide a more gentle and spatially distributed heating.

The above effects clearly demonstrate the need for alternative or supplementary measurements of the energy injected by the AGN. In this paper we report on the long time exposure observation of the elliptical galaxy M84 in the Virgo cluster. We focus on the interaction of the AGN with the ISM and the energy content in the thermodynamical fluctuations generated by the AGN outburst, and we argue that they are waves. An approach to measuring the wave energy that is similar to the one described in this paper has been considered by Sanders & Fabian (2007) in the case of the observations of the Perseus cluster, and in numerical simulations of wave dissipation (Ruszkowski et al. 2004).

2. CHANDRA OBSERVATIONS

Results from the first Chandra observation of M84 (ObsID 803 and exposure time of 25.9 ks) were published in Finoguenov & Jones (2001, 2002). Given the importance of the source in
understanding the AGN feedback, we were granted two more observations (ObsIDs 5908 and 6131), adding 34.9 and 30.9 ks time, respectively. The nominal aim point was ACIS-S, and we only include S3 CCD data here. The initial data reduction is standard; details are presented in Vikhlinin et al. (2005).

For both imaging and spectroscopic analysis, we extracted the counts and the auxiliary information separately from each observation, and added it together at a final stage proportional to the exposure time. The distance-dependent parameters of the emission have been calculated assuming a 17 Mpc distance to M84, at which 1″ corresponds to 5.0 kpc.

2.1. Imaging

The raw cumulative photon count ACIS-S image of M84 in the energy band 0.5–2 keV is shown in Figure 1. In addition to previously identified cavities associated with the radio bubbles, we clearly see structure in the bubbles, which can be approximated by two sets of two bubbles to the north and south of the M84 center. In Figure 2 we compare the X-ray and radio properties of M84. It is clearly seen that while the southern radio bubble is surrounded by the X-ray cocoon, the northern radio bubble broke through the porous X-ray emission at the northern edge. This provides direct evidence of escaping radio plasma from the ISM of the host galaxy into the intergalactic medium.

This paper describes the parameters of these bubbles, with a summary of the results given in Table 1, listing name of the bubble (col. [1]), position of the bubble centroid (col. [2]), bubble axes in kpc (major, minor, assumed projected; col. [3]), effective thickness of bubble walls (col. [4]), total geometrical factor from equation (2) (col. [5]), estimated Mach number from the pressure jump (col. [6]), PV work (enthalpy $H$ is higher by up to a factor of 4, as explained above; col. [7]), and wave energy, calculated using equation (2) with $\gamma = 5/3$ (col. [8]; see below). In calculating the values of columns (7) and (8) we used a three-dimensional integral over the bubbles and a nonparametric fit to the pressure profile of all zones of M84, as explained in § 3. In making the calculation we use the exact pressure prediction at each $dV$ element, assuming a spherical symmetry in the pressure.

Imaging analysis provides information on the bubble appearance, such as centering, size, and orientation, which enter into the volume and surface calculations. The width of the bubble walls is calculated as the ratio between the distances from the bubble

Fig. 1.—Image of M84 in the 0.5–2 keV band. Red circles show the position and size of the four identified bubbles. The image is 2.8′ or 14 kpc wide on a side. [See the electronic edition of the Journal for a color version of this figure.]
center to the outer and inner boundaries; this is used in calculating the wave energetics, and helps to select the regions for subsequent spectral analysis, which we describe next.

Statistics obtained in the combined Chandra observation of M84 requires substantial binning of the data for subsequent spectral analysis. Binning techniques based on Voronoi tessellation methods have been proven to be the most efficient and unbiased way to address the binning issue (e.g., Cappellari & Copin 2003). However, in order to study the waves and bubbles, we need to separate the bubble rims from both the inner and outer medium. To

![Image](image_url)

**Fig. 2.**—Binned raw X-ray image of M84 with radio contours overlaid. For the southern part of M84, radio emission is clearly embedded in the X-rays, while in the north it breaks through the bubbles. The image is 3.6' or 18 kpc wide on a side.

| Bubble Name           | R.A., Decl. (deg; J2000) | Axes (kpc) | \( \lambda/r \) | \( (\lambda/r)(r/R)^3 \) | M (10^57 ergs) | PV Work (10^55 ergs) | Wave Energy (10^55 ergs) |
|-----------------------|--------------------------|------------|----------------|-------------------------|----------------|----------------------|-------------------------|
| Southern Large        | 186.26217, +12.869655    | 2.6, 2.2, 2.2 | 1/7           | 0.2                     | 1.3            | 1.32                 | 0.67                    |
| Southern Small        | 186.26680, +12.882228    | 1.4, 1.5, 1.4 | 1/4           | 0.6                     | 1.3            | 0.30                 | 0.37                    |
| Northern Small        | 186.26876, +12.890701    | 1.3, 1.5, 1.5 | 1/4           | 0.6                     | 1.3            | 0.26                 | 0.35                    |
| Northern Large        | 186.27185, +12.892204    | 2.0, 2.9, 2.9 | 1/7           | 0.2                     | 1.3            | 1.37                 | 0.72                    |

* Axes are major, minor, and assumed projected.
accomplish this task, we produced masks defining large contiguous zones of equal emissivity, which are then subsequently subdivided in order to achieve the selected signal-to-noise ratio using Voronoi tessellation. Previous applications of this technique can be found in Simionescu et al. (2007), and it is somewhat similar to the contour binning technique of Sanders (2006).

3. MAPS

Using the constraints imposed by strong variations in the X-ray surface brightness, we have designed a mask of 130 regions which depict all the important details of M84. This mask optically splits large regions into smaller ones using the Voronoi tessellation method. This method has been previously applied to XMM-Newton observations of M87 (Simionescu et al. 2007) and A3128 (Werner et al. 2007). This is the first application of this method to Chandra data. Results of this analysis were first made available on the Web using a metatable format developed at the German Astrophysical Virtual Observatory (GAVO). This service allows one to view the parameters of the fit, access the quality of the fit, build, view and retrieve any maps, and access the significance of every feature.

For the spectral analysis, we used the APEC model. In addition to the soft emission of M84, we clearly detect harder emission which on smaller scales is centered on M84, as discussed in Finoguenov & Jones (2001), while on large scales it is associated with emission of the Virgo cluster in which M84 is embedded. Thus, we introduced a second APEC model with temperature fixed at 3 keV and a fixed metallicity of 0.3 solar. Having two thermal models substantially reduces our ability to derive the metallicity in M84. Therefore, we have also fixed the metallicity of the APEC component describing the M84 emission at 0.3 solar, which is typical of the regions of M84 with bright X-ray emission.

Since the bubbles are symmetric about their center, but not with respect to the center of X-ray emission in M84, we have adopted a complex procedure for deriving the volumes, which require an estimate of the projected length. All bubble-related features are calculated assuming spherical symmetry relative to the bubble centers (listed in Table 1). Other features are calculated using spherical symmetry relative to the center of the X-ray brightness of M84. The exact details of our volume calculation and selection of the centers of the elements are presented in Mahdavi et al. (2005).

In order to study the fluctuations in pressure and entropy, first we analyze the mean trends, following the procedure outlined in Sanderson et al. (2005), which puts the values of the map on the profile according to the distance to the center of the region, generates a nonparametric fit to the profile (using the R-package) and calculates the residuals. Each region is treated as one point on the profile. Within this procedure small differences in defining the center of the region (e.g., as discussed in Mahdavi et al. 2005) would result in differences in the mean profile, but not in the ratios. In Figure 3 we show the ratio of the observed pressure to the mean pressure profile (left panel) and the analogous quantity for the gas entropy. The fractional rms fluctuations of entropy and pressure caused by the AGN are on the level of 47% and 41%, respectively, with 5% measurement uncertainty. For comparison, in clusters of galaxies similar levels of fluctuation are associated with distortions due to a recent merger (Poole et al. 2007) and have about a 10% occurrence probability at low redshift (Finoguenov et al. 2005, 2007). However, the features associated with cluster mergers appear on much larger spatial scales.

4. HYDRODYNAMICAL SIMULATIONS

In order to gain insights into the bubble physics, we embarked on hydrodynamical simulations. The details of the simulation used here can be found in Brüggen et al. (2005). Here we only summarize the relevant information. The initial conditions for the simulation were taken from the S2 cluster run (Springel et al. 2001) performed with the GADGET code. Starting from these initial conditions (at $z = 0$), we evolved the system for $140$ Myr using the adaptive mesh refinement FLASH code. The full size of the computational domain was $20000 h^{-1}$ Mpc, and the maximum resolution was $1.96 h^{-1}$ kpc. While the cluster atmosphere and ICM parameters differ from those in M84, the initial conditions possess some characteristics that make the simulated system qualitatively similar to M84. In particular, the structure is quite dynamic, the central object moves relative to the surrounding gas, and the temperature in the central parts raises with radius, as in M84.

5. WAVES

The main result from the maps in Figure 3 is the identification of bubble walls with regions of enhanced pressure (by a factor of 1.5) and simultaneously 40% lower entropy. Previously, the presence of shock waves has often been dismissed on the grounds of the low-temperature contrast seen between the bubbles and the surrounding medium. Such a comparison assumed a similarity in the entropy between the bubble walls and the surrounding medium. This is in contradiction to the observed entropy distribution seen in Figure 3, which shows that the gas associated with the bubble walls has low entropy. One would expect higher temperature in the compressed gas, if not for the fact that low-temperature gas is entrained and moved to larger distances from the center, thus partially canceling the effect of adiabatic heating. Thus, the low-temperature contrast may well be consistent with the wave scenario. We estimated that, on the timescale of the bubble expansion ($10^7$ yr), the cooling (timescale of $10^5$ yr) is not important, and the origin of low-entropy gas is due to entrainment from the central regions of M84. The entropy profile in M84 is rather steep, and small gas displacements (compared to the bubble size) are sufficient to reproduce an observed picture.

We thus interpret the overpressured shells seen in M84 as waves propagating away from the sites where the energy has been injected by the AGN. The compression of the gas immediately outside the cavity is released in the form of a weak shock wave. A similar interpretation has also been presented for the Perseus cluster (Fabian et al. 2003) and M87 (Forman et al. 2007). This interpretation is supported by the results of numerical simulations (see Fig. 4). We also note that the observed fractional pressure fluctuations in the “walls” are larger than the fractional density fluctuations, which is consistent with the adiabatic compression scenario. As a proof of concept, in Figure 4 we show a density slice corresponding to a snapshot from an adaptive mesh refinement hydrodynamical simulation of AGN feedback. The images have been unsharp-masked and Gaussian-blurred to enhance the fluctuations. There is a qualitative similarity between this figure and the morphology of M84. This figure shows that multiple outbursts can lead to nested waves, similar to a Russian matryoshka doll. The upper panel corresponds to an earlier epoch, and the snapshots are separated by approximately $2 \times 10^7$ yr. The waves detach from the AGN-inflated cavities, as is clearly seen in the lower panel. The northern cavity is further distorted due to the relative motion between the AGN and the ICM. Interestingly, the evolution of the (nearly) vertical boundary between the northern bubbles seen in the simulation shows that this feature is also a

$^7$ GAVO is accessible at http://www.g-vo.org/ MAXI; for our data, see data release unique identifier (druid) http://www.g-vo.org/MAXI/druid/2.
propagating wave (this is clearly seen in the animated version of the data). A similar feature is located “inside” the northern cavity in M84.

6. ESTIMATING AGN WORK

We estimate the energy carried in the waves using the following approach. The instantaneous energy flux $F$ carried by a wave is given by

$$ F \equiv \frac{P_{\text{wave}}}{S} = \frac{(\delta P)^2}{\rho v_{\text{wave}}}, $$  

(1)

where $v_{\text{wave}}$ is the wave propagation velocity, $P_{\text{wave}}$ is the wave power, $S = 4\pi r^2$, where $r$ is the distance of the wave front from the bubble center, $\rho$ is the ICM density, and $\delta P$ is the pressure fluctuation in the wave front (Landau & Lifshitz 1997; Ruszkowski et al. 2004; Sanders & Fabian 2007). Strictly speaking, equation (1) is valid only for small perturbations, but it should suffice for our estimates, as the inferred Mach number of the waves only slightly exceeds unity (see below). We assume that at any given time the wave front is a sphere, and the instantaneous power of the entire wave is $P_{\text{wave}} = 4\pi r^2 F \text{ erg s}^{-1}$. In the absence of dissipation, this (total) power would remain constant even though $r$, $\rho$, $v_{\text{wave}}$, and $\delta P$ would all vary. The total energy carried by one wave is then

$$ E_{\text{wave}} \sim P_{\text{wave}}\lambda/v_{\text{wave}}, $$  

where $\lambda$ is the wavelength (or approximately the thickness of the pressure fluctuation). Approximating $v_{\text{wave}}$ as the adiabatic sound speed, the final expression for the wave energy is

$$ E_{\text{wave}} \sim 3 \left( \frac{\lambda}{r} \right)^{-1} PV \left( \frac{\delta P}{P} \right)^2 \left( \frac{r}{R} \right)^3, $$  

(2)

where $V$ is the bubble volume, $P$ is an underlying pressure, $R$ is the bubble radius, $r$ is the distance of the wave front from the bubble center, and $\gamma$ is the adiabatic index of the gas in the vicinity of the wave. The pressure morphology of the source suggests that the ratio of the wave thicknesses to the radii of the wave fronts is approximately in the range $\sim 1/7$ to $1/4$, depending on the bubble position (e.g., $\sim 1/4$ for the small bubbles, $\sim 1/7$ for the large bubbles). If $r \sim R$, and using our observation of $\delta P/P \sim 1$, this would suggest that $E_{\text{wave}}$ is of the order of $PV$. Even if the bubble energy is greater than $PV$ by a few, one wave carries a significant fraction of the outburst energy. The result of this analysis is shown in Table 1, where wave energy is compared to $PV$ work. The energy carried by the waves can significantly contribute to the overall energy budget. Note also that the smaller inner outbursts have larger wave-to-bubble energy ratios.

Fig. 3.—Ratio of the observed pressure (left) and entropy (right) in M84 to their corresponding average profiles. The values vary between 0.5 and 2. One can identify the bubble walls with a factor of 1.5 higher pressure and 40% lower entropy. Each image is $2.8' \times 3.8'$ (14 $\times$ 19 kpc) in size. [See the electronic edition of the Journal for a color version of this figure.]
In addition to energy carried by the wave, we can calculate the energy deposition into the IGM associated with supersonic wave motion,

\[ dQ = TdS = \frac{1}{\gamma - 1} \left( \frac{kT}{\mu m_p} \right) \frac{dS_X}{S_X}, \tag{3} \]

where \( S_X = kT \rho^{1-\gamma} \) is a common definition of the entropy among X-ray observers. For the value of Mach number of 1.3 measured for M84 bubbles, and employing the Rankine-Hugoniot adiabat shock adiabat to derive the change in the entropy,

\[ 1 + \frac{dS_X}{S_X} = \frac{[2\gamma M^2 - (\gamma - 1)][(\gamma - 1)M^2 + 2]}{(\gamma + 1)^{\gamma+1} M^{2\gamma}}, \tag{4} \]

\( dS_X/S_X = 0.013 \), and the full energy deposition \( dQ dM_{\text{gas}} \) is a few percent of the total wave energy. The maximum deposition of energy occurs near the center of M84 and in the direction perpendicular to the bubble outflow, where the cooling losses are also largest. This probably results from an interference of waves coming from northern and southern bubbles and is an important channel of energy deposition into the central parts of M84 IGM.

We note that using

\[ \frac{dS_X}{S_X} = \frac{dP}{\rho} - \gamma \frac{d\rho}{\rho}, \tag{5} \]

d\( Q dM_{\text{gas}} \) can be rewritten as

\[ dQ dM_{\text{gas}} = \int \frac{dP}{\gamma - 1} dV - \int \frac{\gamma}{\gamma - 1} \frac{d\rho}{\rho} dV. \tag{6} \]

The second part of the equation is negligible in the case of strong shock (\( M > 1000 \)), which leads to the equation used by Graham et al. (2008). We note, however, that in our case the two terms are nearly equal, and in the case of adiabatic compression they exactly cancel out. The total heating supplied by the AGN, when compared to \( 9.4 \times 10^{40} \) bolometric luminosity associated with extended emission of M84 (not counting the contributions...
from the AGN and LMXB), requires bubble recurrence on a $1.8 \times 10^7$ yr scale to entirely compensate for the radiative energy losses, similar to what is actually observed in M84.

The morphology of the southern shells seen in the data suggests that the expansion velocity is comparable to the velocity of M84 relative to the ICM. A typical velocity of a cluster galaxy is expected to be mildly supersonic (Faltenbacher et al. 2006). This is because $c_s^2 = \frac{\gamma P_{\text{gas}}}{\rho} = \gamma \sigma_{\text{gal},1D}^2 = \gamma \sigma_{\text{gal},3D}^2 = \gamma \sigma_{\text{gal}}^2/3$, where $\sigma_{\text{gal},1D}$ and $\sigma_{\text{gal},3D}$ are the one-dimensional and three-dimensional gas internal velocity dispersions, respectively, and $\sigma_{\text{gal}}$ is the galaxy velocity dispersion (Sarazin 1988). The last approximate equality comes from the assumption of equipartition between the gas and the galaxies. For $\gamma = 5/3$, this leads to the galaxy Mach number $\sim 1.34$. This in turn suggests that the shell expansion may be, at least initially, supersonic. If so, this would also be consistent with an estimate of the Mach number of the waves. If the pressure fluctuation is $\sim \delta P/P \sim 1$, as suggested by our observations, then for $\gamma = 5/3$, the Mach number of the waves is $M \sim (1 + \gamma^{-1}) x/2 + 1)^{1/2} \sim 1.34$, in qualitative agreement with the estimate above.

7. CONCLUSIONS
We have analyzed a deep Chandra observation of the AGN feedback in the Virgo elliptical galaxy M84. We have applied a constrained Voronoi tessellation binning method to the Chandra data. Our main results are (1) the AGN outflow is mildly supersonic; (2) the nonthermal plasma from the AGN-inflated cavities appears to be porous, with nonthermal particles escaping from the cavities; (3) concentric density perturbations (weak shock waves) are present, and their morphology is qualitatively consistent with the results of numerical simulations; and (4) we have estimated the mechanical energy in the waves and found that it may contribute substantially to the overall mechanical energy delivered by the AGN.

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