Feedback under the microscope II: heating, gas uplift, and mixing in the nearest cluster core

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ABSTRACT

Using a combination of deep (574 ks) Chandra data, XMM-Newton high-resolution spectra, and optical Hα+[N ii] images, we study the nature and spatial distribution of the multiphase plasma in M 87. Our results provide direct observational evidence of ‘radio mode’ AGN feedback in action, stripping the central galaxy of its lowest entropy gas and therefore preventing star-formation. This low entropy gas was entrained with and uplifted by the buoyantly rising relativistic plasma, forming long “arms”. A number of arguments suggest that these arms are oriented within 15°–30° of our line-of-sight. The mass of the uplifted gas in the arms is comparable to the gas mass in the approximately spherically symmetric 3.8 kpc core, demonstrating that the AGN has a profound effect on its immediate surroundings. The coolest X-ray emitting gas in M 87 has a temperature of ∼0.5 keV and is spatially coincident with Hα+[N ii] nebulae, forming a multiphase medium where the cooler gas phases are arranged in magnetized filaments. We place strong upper limits of 0.06 M⊙/yr (at 95 per cent confidence) on the amount of plasma cooling radiatively from 0.5 to 0.25 keV and show that a uniform, volume-averaged heating mechanism could not be preventing the cool gas from further cooling. All of the bright Hα filaments in M 87 appear in the downstream region of the < 3 Myr old shock front, at smaller radii than ~0.6′. We suggest that shocks induce shearing around the filaments, thereby promoting mixing of the cold gas with the ambient hot ICM via instabilities. By bringing hot thermal particles into contact with the cool, line-emitting gas, mixing can supply the power and ionizing particles needed to explain the observed optical spectra. Furthermore, mixing of the coolest X-ray emitting plasma with the cold optical line emitting filamentary gas promotes efficient conduction between the two phases, allowing non-radiative cooling which could explain the lack of X-ray gas with temperatures under 0.5 keV.

Key words: X-rays: galaxies: clusters – galaxies: individual: M 87 – galaxies: intergalactic medium – cooling flows

1 INTRODUCTION

If the energy radiated away at the centres of so-called “cool-core” clusters of galaxies, which show sharp X-ray surface brightness peaks and central temperature dips, came only from the thermal energy of the hot, diffuse intra-cluster medium (ICM), the ICM would cool and form stars at rates orders of magnitude below what the observations suggest (see [Peterson & Fabian 2006] for a review). It is currently believed that the energy which offsets the cooling is provided by the interaction between the active galactic nuclei

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Perseus, M 87, Centaurus, and Hydra A revealed AGN induced deep observations of nearby bright cooling core clusters such as can provide enough energy to prevent catastrophic cooling. Recent AGN in the central dominant galaxies and the ICM (see Chu-also e.g. Brüggen & Kaiser 2002; Kaiser 2003; Brüggen 2003; De all of which could provide heating to the cooling core region (see lent motion in the wake, and potential energy of the uplifted gas, bubbles dissipate energy into sound waves, internal waves, turbu-
cools. Churazov et al. (2001) suggested that the buoyantly rising gas from the centre of the galaxy, which then further adiabatically cools. Churazov et al. (2001) suggested that the buoyantly rising bubbles dissipate energy into sound waves, internal waves, turbu-
lent motion in the wake, and potential energy of the uplifted gas, all of which could provide heating to the cooling core region (see also e.g. Brüggen & Kaiser 2002; Kaiser 2003; Brüggen 2003; De Young 2003; Ruszkowski et al. 2004a,b; Heinz & Churazov 2005).

Observations with Chandra and XMM-Newton greatly enhanced our view of M 87. Using XMM-Newton observations, Belsole et al. (2001), Matsushita et al. (2002), and Molendi (2002) showed that the regions associated with radio arms have two-temperature (in the ranges of $kT \sim 0.8–1.1$ keV and $kT \sim 1.6–2.5$ keV) or multi-temperature structure. However, plasma below 0.8 keV is largely absent (Böhringer et al. 2002; Sakelliou et al. 2002). Young et al. (2002) analyzed an early, relatively short (40 ks) Chandra observation which showed cavities and edges in the hot plasma. They compared the X-ray morphology with the 6 cm radio (Hines et al. 1989) and Hα+[N ii] emission (Sparks et al. 1993) and showed that the optical filaments lie outside of X-ray cavities filled with radio plasma; some are along the edges of the cavities, and several optical filaments coincide with knots of cooler X-ray gas. Using a longer (~150 ks) Chandra observation, Sparks et al. (2004) studied the relation of the X-ray and optical filaments and concluded that electron conduction from the hot X-ray emitting plasma to the cooler phase provides a quantitatively acceptable energy source for the optical filaments. Using the same Chandra data, Forman et al. (2005) identified shock fronts associated with an AGN outburst about $1\lesssim t \lesssim 10^7$ yr ago. They argued that shock fronts may be the most significant channel for heating (i.e., entropy increase) of the ICM near to the AGN.

Subsequent Chandra observations increased the total exposure time to 500 ks, which allowed Forman et al. (2007) to resolve a web of filamentary structure in both X-ray arms. Both arms show narrow filaments, with a length-to-width ratio of up to ~50. However, while the Southwestern arm has only a single set of filaments, the Eastern arm shows multiple sets of filaments and bubbles, increasing in scale with the distance from the centre. The high spatial resolution of Chandra also highlights the fact that while the Eastern X-ray arm is cospatial with the radio arm, the radio emission bends around and avoids the Southwestern X-ray arm. A residual image of M 87 showing the inner cavities and the X-ray arms obtained using all Chandra ACIS-I data is shown in Fig. 11 (from Million et al. 2010, together with the 90 cm radio image by Owen et al. 2000). The temperature structure and metallicity of the X-ray arms was studied in detail by Simionescu et al. (2008a) using deep (120 ks) XMM-Newton data. These authors confirmed that the arms are multiphase with a temperature distribution between 0.6–
3.2 keV. This temperature distribution is also consistent with that found by spectral fits to the XMM-Newton Reflection Grating Spectrometer (RGS) data (Werner et al. 2006), which show the presence of weak Fe xxv lines (Simionescu et al. 2008) estimate the total mass of gas below 1.5 keV, most of which was uplifted by the AGN, as $5\times10^9 M_{\odot}$.

This is the second in a series of papers (following the work by Million et al. 2010 hereafter Paper I) presenting detailed spatially resolved spectroscopy of M 87, exploiting the superb spatial resolution and excellent photon statistics of the deep (574 ks) Chandra observation, to study AGN feedback and ICM physics. In this paper, we study for the first time the detailed nature and the spatial distribution of the multiphase plasma associated with the X-ray arms. Chandra allows us to study detailed structure in the cooler phases at a much higher spatial resolution than is possible with XMM-Newton. Our data allow us to sample well the small substructure seen in the Chandra images, map the spatial distribution of the individual temperature components and compare it with new Hα images obtained at the Lick Observatory, and archival data from the Hubble Space Telescope (HST). In Section 2, we describe the data reduction and analysis; in Section 3, we present the results of the observations; in Section 4, we determine the physical properties of the cooler plasma phases and discuss the uplift of the low entropy gas from the bottom of the gravitational potential well, and effects of shocks and mixing. Finally, in Section 5, we summarize our conclusions.

A distance to M 87 of 16.1 Mpc (Tonry et al. 2001) implies a linear scale of 4.7 kpc arcmin$^{-1}$. All errors are quoted at the 68 per cent confidence level for one interesting parameter.
2 DATA REDUCTION AND ANALYSIS

2.1 Chandra data

The Chandra observations of M 87 were taken between July 2002 and November 2005 using the Advanced CCD Imaging Spectrometer (ACIS). The observations are listed in Table 1. The total net exposure time after cleaning is 574 ks. We follow the data reduction procedure described in Paper I (see also Million & Allen 2009; Million et al. 2009).

The individual regions for the spectral analysis were determined using the Contour Binning algorithm (Sanders 2006), which groups neighboring pixels of similar surface brightness until a desired signal-to-noise threshold is met. In order to have small enough regions to resolve substructure and still have enough counts to fit a simple multi-temperature model, we adopted a signal-to-noise ratio of 50. The total number of regions in this analysis is ~6000, with a total number of ~15,000,000 net counts.

Background spectra for the appropriate detector regions were extracted from the blank-sky fields available from the Chandra X-ray Center. These were normalized by the ratio of the observed and blank-sky count rates in the 9.5 – 12 keV band (the statistical uncertainty in the observed 9.5 – 12 keV flux is less than 5 per cent in all cases). The background level in these observations is low and represents only a marginal source of systematic uncertainty in the determined quantities.

Spectral modeling has been performed with the SPEX package (Kaasstra et al. 1996). SPEX uses an updated version of the MEKAL plasma model with respect to XSPEC. We analyze data in the 0.6–7.0 keV band. To investigate the multi-temperature structure and map the spatial distribution of plasmas at different temperatures, we fit to each bin a model consisting of collisionally ionized equilibrium plasmas at four fixed temperatures, with variable normalizations and common metallicity. This method was introduced by Sanders et al. (2004) in the analysis of deep Chandra observations of the Perseus cluster. For M 87, the temperatures are fixed at 0.5, 1.0, 2.0, and 3.0 keV. The temperatures of the coolest and hottest components were selected based on previous multi-temperature analysis of XMM-Newton RGS and EPIC data (Werner et al. 2006; Simionescu et al. 2008). We also searched for a 0.25 keV component in our spectral fits, but did not detect any emission at this temperature. The temperatures of the individual spectral components are sufficiently far apart that the spectral analysis can constrain their emission measures if they are simultaneously present in the same extraction region. The overall metallicity in each region is free to vary. The O/Fe ratio is fixed at 0.59 Solar, Ne/Fe at 1.20 Solar, and the Mg/Fe at 0.60 Solar, as determined from XMM-Newton RGS spectra (Werner et al. 2006). The Galactic absorption toward M 87 is modelled as neutral gas with Solar abundances with a column density fixed at \( N_H = 1.94 \times 10^{20} \) cm\(^{-2}\), the value determined by the Leiden/Argentine/Bonn (LAB) Survey of Galactic H\(_2\) (Kalberla et al. 2005). Throughout the paper, abundances are given with respect to the “proto-solar values” by Lodders (2003), which are for O, Ne, and Fe approximately 30 per cent lower than the values given by Anders & Grevesse (1998).

2.2 XMM-Newton RGS data

The multi-temperature structure of the hot plasma in and around M 87 exhibits a complex set of spectral lines that cannot be modelled by a single-temperature spectral model (Sakelliou et al. 2002).
In order to confirm that our simple four-temperature model describes the temperature structure of M 87 well, we fit the same model to the XMM-Newton RGS spectra.

The XMM-Newton RGS data were obtained in January 2005, with a net exposure time of 84 ks. The data were processed as described in [Werner et al. (2006)]. Spectra were extracted from a 1.1′ wide extraction region, centred at the core of the galaxy. Because the RGS operates without a slit, it collects all photons from within the 1.1′×12′ field of view. Line photons originating at angle $\Delta \theta$ (in arcminutes) along the dispersion direction are shifted in wavelength by $\Delta \lambda = 0.138 \Delta \theta \text{ Å}$. Therefore, every line is broadened by the spatial extent of the source. To account for this spatial broadening in our spectral model, we produce a predicted line spread function (LSF) by convolving the RGS response with the surface brightness profile of the galaxy derived from the EPIC/MOS1 image along the dispersion direction. Because the radial profile of a particular spectral line can be different from the overall radial surface brightness profile, the line profile is multiplied by a scale factor $s$, which is the ratio of the observed LSF to the expected LSF. This scale factor is a free parameter in the spectral fit.

We fit the spectra in the 8–38 Å band with the same four-temperature model fitted to the Chandra data, with an additional 0.25 keV component included to determine an upper limit on the amount of such cool plasma. We have also separately fitted the RGS data.
data with a model consisting of four isobaric cooling flows with elemental abundances tied between the models (similar to one of the models used for the Centaurus cluster in Sanders et al. 2008). In this case, we model separately gas cooling from 3 keV to 2 keV, from 2 keV to 1 keV, from 1 keV to 0.5 keV, and from 0.5 keV to 0.25 keV. The central AGN cannot be excluded from the RGS data of the core of the galaxy and also needs to be accounted for. We model the AGN spectrum with a power-law of a photon index $\gamma = 1.95$ and a 2–10 keV luminosity of $L_X = 1.15 \times 10^{45}$ erg s$^{-1}$ (Werner et al. 2006).

2.3 H$\alpha$ data

Narrow-band H$\alpha$ imaging (central wavelength 6606 Å, FWHM 75 Å) of M 87 was carried out using the Shane 3 m telescope at Lick Observatory on March 26th, 2009. The total integration time was 24 ks, split into 20 exposures using a dither pattern with $\sim 5''$ offsets. We also acquired 1200 seconds of R band imaging, also split into 20 exposures. The data were processed using the pipeline of Erben et al. (2005). A constant background was subtracted, estimated from the region of the image with the lowest counts. The images were registered with scamp (Bertin 2006), and resampled and combined with swarp (Bertin et al. 2002). The seeing of the coadded images is about 2$''$.

To study the morphology of the brighter H$\alpha$ filaments in the cluster core, we have also analyzed two H$\alpha$ images available in the HST archive. Both images were taken with WFPC2, placing the core onto the Planetary Camera. The Southwestern region was imaged with the Wide Field Camera for only 2700 seconds (proposal ID: 5122, PI Ford), and is not as deep as our ground-based image. The Northwestern region was imaged significantly longer (13900 seconds, proposal ID: 6296, PI Ford).

3 RESULTS

3.1 Spatial distribution of the X-ray gas

Fig. 2 shows the spatial distribution of the emission measures for the four individual temperature components (0.5, 1.0, 2.0, and 3.0 keV) obtained from the Chandra data. The top left panel shows an interesting result: the map reveals the presence of gas with a temperature of $kT \sim 0.5$ keV to the North of the jet in the core of the galaxy, in the Southwestern arm, and in a horseshoe like filament to the Southeast of the core outside of the mushroom shaped Eastern radio arm (radio contours are overplotted in the top right panel of Fig. 3). No 0.5 keV gas with significance higher than 3$\sigma$ is present within the Eastern radio arm. While all the detected 0.5 keV plasma in the core and in the Southeastern horseshoe is within the RGS extraction region (see the left panel of Fig. 1), the Southwestern arm is outside of the area covered by the present RGS data.

The spatial distribution of the $\sim 1$ keV plasma seen in the top right panel of Fig. 2 correlates with the radio emission and is very similar to the morphology of the X-ray arms seen clearly in Fig. 1. In the core, the 1 keV plasma forms a prominent ridge to the North of the AGN, which is cospatial with 0.5 keV plasma and H$\alpha$+[N II] emission (see below). Based on two-temperature spectral fits to XMM-Newton data it has been shown that the X-ray arms are relatively isothermal at $\sim 1$ keV (Molendi 2002, Simionescu et al. 2008) and our spectral fits to the Southwestern X-ray arm confirm that its temperature is constant as a function of radius (see Fig. 5). Most of the Eastern radio arm contains $\sim 1$ keV plasma, a large amount of which is also present to the South of the “stem of the radio mushroom” where the 0.5 keV horseshoe is observed. The brightest part of the Southwestern radio arm is not spatially coincident with the 0.5 keV and 1 keV plasma, but it bends around the cooler X-ray gas. On the Southwest, just outside of the core region, the 1 keV plasma forms a narrow and remarkably straight and smooth filament, which broadens with increasing distance from the core. At around 3$'$, which is the approximate distance of the circular shock front described in Paper I and by Forman et al. (2007), the distribution of 1 keV gas broadens, and at 4.5$'$ it starts to bend to the Southeast.

The spatial distribution of the plasma at $\sim 2$ keV is, in comparison, remarkably symmetric and only slightly elongated in the direction of the X-ray arms. A knot of $\sim 3$ keV plasma is present at the inner edge of the X-ray cavity South of the core, at the bottom of the bright radio cocoon, which Forman et al. (2005) identified as a “bud”. This 3 keV plasma is most probably associated with a shock front at the radius of 0.6$'$ (Forman et al. 2007, Paper I, see also the right panel of Fig. 5).

The fraction of the emission measure of cooler gas (1 keV and 0.5 keV) in the X-ray arms with respect to the total emission measure is 10–35 per cent, consistent with the results obtained by fitting a differential emission measure distribution to XMM-Newton data by Simionescu et al. (2008). The spatial distribution of the coolest gas phases is also in good agreement with that found in the XMM-Newton data analysis (Simionescu et al. 2008), but is revealed by Chandra with a strikingly better spatial resolution.

The elemental abundances obtained from the fits are likely to be biased due to the limitations of our model, which has its temperatures fixed at specific values (detailed study of the metallicity will be presented in Million et al. in prep.; see also Paper I and Simionescu et al. 2008).
3.2 Morphology of the Hα nebulae: new clues about their powering

The left panel of Fig. 4 shows an excerpt of the Hα+[N ii] image obtained at the Lick Observatory after subtraction of the scaled R-band continuum image. Owing to the large depth, our data reveal a previously undiscovered horseshoe-like filament of Hα+[N ii] emission to the Southeast of the core. The feature is detected at a mean level of 5σ above the sky. Fig. 4 shows that the spatial distribution of the Hα+[N ii] emission is remarkably similar to that of the 0.5 keV plasma, both in the core and in the Southeastern horseshoe-like region. Except for a small knot of Hα+[N ii] emission in the “cap of the mushroom” (see Gavazzi et al. 2000), the Eastern radio arm is devoid of observable Hα filaments. As mentioned above, the Eastern radio arm is also devoid of any detectable 0.5 keV emission. Our Lick Observatory data (Fig. 4) and the HST data (Fig. 5) unfortunately do not cover the Southwestern X-ray arm.

Fig. 5 shows an Hα image for the innermost 2′×2′ region of M 87 from HST next to a pressure map obtained in Paper I by using Chandra data. In the pressure map we see a discontinuity, a likely shock front, at a radius of 0.6′. The Hα image shows that all the bright Hα filaments appear in the downstream region of the shock. The arrows identify the bright Hα features furthest from the centre, at the edges of apparently underpressured X-ray cavities, and a bright Hα “knee” on the Southeast.
to the shock front, bright in the downstream region and faint in the upstream. Upstream of the shock front, the Southeastern Hα filament continues at a much lower surface brightness and forms the prominent horseshoe. On the Hα image, we identify with arrows the bright features furthest from the centre, at the edges of X-ray cavities, and a bright Hα “knee” on the Southeast. The same arrows are plotted in the pressure map.

3.3 High-resolution XMM-Newton RGS spectra

To confirm the presence of the coolest gas phases indicated by fitting the Chandra data and to verify that the simple four-temperature model fits the data sufficiently well, we also analyze the XMM-Newton RGS high-resolution line spectra. The results of the five-temperature fit to the RGS data are listed in Table 2 and the best fit model to the spectra is shown in Fig. 6.

The emission measures for the 2 keV and 1 keV phases obtained by the RGS are consistent with those from the Chandra maps for the area covered by the gratings. The emission measure of the 0.5 keV phase obtained using the RGS is higher by a factor of 3 than the value from the Chandra map. The sensitivity of Chandra in the 0.6–7 keV band to 0.5 keV emission in these moderate S/N spectra is limited and if we only consider regions where the 0.5 keV component was detected at larger than the 99.7% confidence level then we miss the cool emission in some regions. By including all regions detected at the 68% confidence the 0.5 keV features in the map become wider and the agreement between the emission measures from Chandra and RGS improves.

The lack of O vi lines provides strong constraints on the amount of 0.25 keV plasma. The 95 per cent upper limit for its emission measure is lower by a factor of 11 than the emission measure of the 0.5 keV plasma.

To get constraints on the amount of radiative cooling, we also fit the RGS spectra with a set of cooling flow models (see Table 2). If the plasma would cool isobarically in the absence of heating, the best fit mass deposition rates would be the same in the different temperature ranges. However, the mass deposition rates are decreasing as a function of temperature and for the gas cooling from 0.5 keV to 0.25 keV we determine a tight 95 per cent upper limit of $M = 0.06 M_\odot/yr$.

4 DISCUSSION

4.1 Orientation of the X-ray arms

The inferred properties of the X-ray arms depend critically on their orientation with respect to our line-of-sight. Based on HST observations of the superluminal motion in the jet of M 87, Biretta et al. (1999) concluded that the position angle of the jet is $< 19^\circ$ from our line-of-sight. The two large, partially overlapping, outer radio lobes of M 87 (the diffuse structures which embed the more collimated, brighter radio arms seen in the right panel of Fig. 1) and in Owen et al. (2000) are also probably oriented close to our line-of-sight. It is likely that the Southern radio lobe is positioned towards us and the Northern lobe is oriented away from us. This picture is supported by the observation of polarized flux from the Southern lobe (Andernach et al. 1979), which shows that the Faraday depth towards it is likely to be small. The radius of the large lobes/bubbles is $\sim 22$ kpc and their approximate centres are in projection 26 kpc apart. Assuming that the physical distance between the centres of the bubbles is at least twice their radius, a conservative limit for the orientation of the axis along which the bubbles rise is $< 35^\circ$ from our line-of-sight. The Southwestern radio arm appears to “merge” into the Southern lobe indicating that its orientation is similar to that of the two large bubbles. Although the relation of the Eastern radio arm to the outer lobe is less clear, the most likely orientation of both X-ray and radio arms is approximately anti-parallel and far from the plane of the sky.

![Figure 6](image.png)

Table 2. Best fit parameters for a five-temperature fit and a four-cooling-flow model fit to the high-resolution RGS spectra extracted from a 1.1′ wide region centred on the core of M 87. Emission measures, $Y = \int n_e n_i dV$, are given in $10^{63}$ cm$^{-3}$. The scale factor $s$ is the ratio of the observed LSF to the expected LSF based on the overall radial surface brightness profile. The upper limits are quoted at their 95 per cent confidence level. Abundances are quoted with respect to the proto-solar values of Lodders (2003).

| Parameter | 5T-model | 4-c.f. model |
|-----------|----------|-------------|
| $Y_{0.25 keV}$ | $< 0.07$ | – |
| $Y_{0.50 keV}$ | $0.79 \pm 0.05$ | – |
| $M_{0.5–0.25 keV}$ | – | $< 0.06$ |
| $Y_{1.00 keV}$ | $7.1 \pm 0.3$ | – |
| $M_{1.0–0.50 keV}$ | – | $0.90 \pm 0.03$ |
| $Y_{2.00 keV}$ | $56.3 \pm 1.3$ | – |
| $M_{2.0–1.00 keV}$ | – | $3.79 \pm 0.25$ |
| $Y_{3.00 keV}$ | $< 2.4$ | – |
| $M_{3.0–2.00 keV}$ | – | $6.03 \pm 0.21$ |
| s | $2.21 \pm 0.10$ | $2.19 \pm 0.11$ |
| C | $0.75 \pm 0.21$ | $0.82 \pm 0.22$ |
| N | $1.9 \pm 0.3$ | $2.0 \pm 0.3$ |
| O | $0.79 \pm 0.04$ | $0.84 \pm 0.04$ |
| Ne | $1.92 \pm 0.13$ | $1.92 \pm 0.13$ |
| Mg | $1.25 \pm 0.15$ | $1.26 \pm 0.13$ |
| Fe | $1.3 \pm 0.04$ | $1.39 \pm 0.05$ |
| Ni | $0.9 \pm 0.3$ | $0.9 \pm 0.3$ |
of this figure shows the radial entropy profiles calculated as $S = kT/n_e^2$. The top panel shows the cooling time profiles calculated as the gas enthalpy divided by the energy lost per unit volume of the plasma:

$$\tau_{\text{cool}} = \frac{\frac{3}{2}(n_e + n_i)kT}{n_en_i\Lambda(T)}.$$  

(1)

where the ion number density $n_i = 0.92n_e$ and $\Lambda(T)$ is the cooling function for Solar metallicity tabulated by Sutherland & Dopita (1993). Cooling functions based on more up to date plasma codes (Schure et al. 2009) predict for the 0.5 keV plasma a 9 per cent higher cooling rate.

If the arms lie in the plane of the sky, then the small line-of-sight depths of the emitting volumes in Fig. 8 indicate that the 1 keV gas is not volume filling at most radii, including the core of the galaxy. The 1 keV gas is then made of small blobs and filaments with an entropy smaller than the lowest entropy of the ambient medium in the centre of the galaxy (see Fig. 7). This would mean, as pointed out by Molendi (2002), that the cool blobs/filaments can hardly originate from the adiabatic evolution of the hot-phase gas entrained by buoyant radio bubbles, as suggested by Churazov et al. (2001). However, if the arms are oriented close to our line-of-sight, the physical picture changes.

For the likely angles of 15°–30° from our line-of-sight, both the radial distribution of the gas entropy and the distribution of the depths of the emitting volumes of the 1 keV component give a more consistent picture with other observables. The 1 keV plasma appears to be mostly volume filling, except in regions where the X-ray images reveal cavities. Its cooling time is $>1.5 \times 10^8$ yr, which is comparable to or longer than the uplift time. Moreover, by taking the projection effects properly into account, the apparent large angle between the current direction of the jet and the Southwestern arm translates into a much smaller physical angle.

The inferred spatial distribution of the depths of the emitting volumes (see Fig. 8) indicates that the orientation angle of the filament is not constant and at certain positions the arms are folded along our line-of-sight. The Southwestern arm appears to be folded at the projected radius of 3.4′, where the arm divides into two filaments (see Fig. 1). The Eastern arm appears to have folds at ~2.1′ and its line-of-sight depth increases in the cap of the mushroom. We caution that because of the strongly simplified assumptions the values for the depths quoted in the figures are approximate numbers only.

If the uplift of the low entropy plasma were strictly adiabatic, then the temperature of the arms would decrease as a function of radius. However, as shown by Molendi (2002), Simionescu et al. (2008), and in Fig. 3 using a two-temperature model, the average temperature of the arms is remarkably constant. The constant temperature implies rising entropy with radius and suggests that conduction plays an important role in the thermal evolution of the arms.

The estimated total mass of 1 keV gas in the arms is between $6-9 \times 10^8 M_\odot$, which given the uncertainties is remarkably similar to the total gas mass of $6.3 \times 10^8 M_\odot$ within the innermost 3.8 kpc region (0.8′ in the plane of the sky), where the X-ray emission is relatively spherically symmetric. Outside of this radius, all the ~1 keV gas is distributed along the two X-ray arms. If the entropy of the arms is increasing due to heat conduction, then most of the $6-9 \times 10^8 M_\odot$ of ~1 keV plasma might have been uplifted from within the innermost approximately spherical 3.8 kpc region of the galaxy. While this is a large fraction of the total gas mass in the core of the cluster, it is only a fraction of the uplifted gas mass observed in more massive clusters; e.g. the inferred mass of the uplifted gas in Hydra A is $1.6-6.1 \times 10^9 M_\odot$ (Simionescu et al.)
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Figure 8. Maps of the line-of-sight depths in kpc for the emitting volumes of 1 keV plasma for orientation angles of 90° (top left panel), 30° (top right panel), and 15° (bottom left panel) from our line-of-sight. The map on the bottom right panel shows the line-of-sight depth distribution of the 0.5 keV component for an orientation angle of 30° from our line-of-sight. All the panels show the same 10.36′×9.25′ field.

Though seen with great clarity in our study, the physics of gas uplift in M 87 is by no means extreme. Many brightest cluster galaxies can be expected to be similarly efficient in evacuating their lowest entropy plasma during AGN outbursts.

By assuming that the outer radio halo is a spherical bubble of hot plasma undergoing a steady energy input from the jet, Owen et al. (2000) estimated its age to ∼10⁸ yr. However, if the radio halo consists of two bubbles rising buoyantly in the hot ICM, then the outer radio lobes are likely to be older. The age of the radio and X-ray arms estimated by Churazov et al. (2001) is a few times 10⁸ yr. However, if the whole Southwestern arm originated in a single uplift following an AGN outburst, then for an orientation angle of <30° from our line-of-sight, its length is >60 kpc, which assuming an uplift velocity of 400 km s⁻¹ implies an age of >1.5 × 10⁸ yr. The age of the observed structures is thus greater than previously thought.

4.3 Implications for gas motions in the ICM

The NW edge of the Southwestern X-ray arm is remarkably smooth out to the radius of ∼3.3′ and the filament is surprisingly straight for a distance of over 2′. This strongly suggests that the gas mo-
tions cannot be very turbulent in either phase. The lack of strong turbulence in the ICM has been inferred previously based on the straightness of the Hα filaments in the Perseus cluster (Fabian et al. 2003), and strong upper limits on turbulent velocities were placed based on resonance scattering in NGC 4636 (Werner et al. 2009) and turbulent line broadening in Abell 1835 (Sanders et al. 2010b).

The bending of the X-ray arms of M 87 at larger radii might be caused by gas sloshing, which creates a spiral like shear structure in the ICM over a scale of 0.1 kpc. Therefore, instead of having a high shear in the regions where the emission is observed, we assume that the gas is in pressure equilibrium with the surrounding 1 keV gas and that the gas at 2 keV cools non-radiatively by mixing. Sanders et al. (2008, 2010a) reached similar conclusions for a sample of cool core clusters. The coolest X-ray plasma in M 87 might cool non-radiatively by mixing with the cold optical line emitting gas, allowing efficient conduction between the two phases (Fabian et al. 2002; Soker et al. 2003). As indicated by the fact that all the bright Hα+[NII] filaments end at the innermost shock front, this mixing might be promoted by the shock, which induces enhanced shear motions, and might also power the detected optical and UV line emission (see the next section).

### 4.4 The coolest X-ray emitting phase

The total mass of ~0.5 keV gas in M 87 is at least $7 \times 10^6 M_\odot$. Because we calculate the mass of the 0.5 keV component only in spatial regions where it was detected at higher than the 99.7 per cent confidence, this value is a conservative lower limit. The inferred small line-of-sight depths of the emitting volumes of the 0.5 keV component imply that the coolest X-ray emitting gas is not volume filling, but forms a multi-phase medium together with both the hotter X-ray emitting and the cold Hα emitting gas phases. Soft band X-ray images (Forman et al. 2007) reveal that this cooler gas phase forms a network of filaments, which spatially coincide with Hα filaments (Sparks et al. 2004) and soft X-ray gas associated with Hα filaments. We have also observed the Perseus cluster and in 2A 0335+096 (Sanders & Fabian 2007; Sanders et al. 2009).

One of the most prominent regions in M 87 occupied by multiphase plasma is a ridge to the North of the jet, which contains 2 keV, 1 keV, 0.5 keV, and Hα gas. This region is just outside of the inner radio cocoon and possibly contributes to the confinement of the radio plasma on the Northern side and to the depolarization seen there by Owen et al. (1999). The depolarization of the radio emission in this region overlapping with the filaments indicates that the magnetic fields are disordered on scales less than 0.1 kpc. Therefore, it is likely that the Hα filaments consist of many narrow magnetized threads, which are not perfectly aligned and are small compared to the observed beam. Depolarization of the radio emission at regions containing Hα and soft X-ray emission has been previously observed in the Centaurus cluster (Taylor et al. 2007).

#### 4.4.1 Limits on cooling and constraints on viable heating mechanisms

Even though the cooling time of the ~0.5 keV gas is relatively short (see the top panel of Fig. 7), no X-ray emitting plasma below 0.5 keV is observed in M 87. The 95 per cent confidence upper limit for the emission measure of 0.25 keV plasma based on the non-detection of O vi lines with RGS is $Y = \int \rho u_d dV = 7 \times 10^{67} \text{cm}^{-3}$, which is only 9 per cent of the emission measure of the 0.5 keV plasma. Therefore, assuming pressure equilibrium between different gas phases, the mass of the 0.25 keV phase is at least 22 times lower than the mass of the 0.5 keV plasma. Assuming the 1 keV gas is isobarically cooling to 0.5 keV, its best fit mass deposition rate is $M = 0.9 M_\odot \text{yr}^{-1}$, which is 15 times larger than the 95 per cent confidence upper limit for the mass deposition rate from 0.5 keV to 0.25 keV. The upper limits on gas cooling below 0.5 keV rely on the O vi lines and thus on the O abundance of the cool gas, which we assumed to be the same as that of the hotter phase which is fairly constant across the core (Werner et al. 2006). For significant amounts of gas cooling radiatively below 0.5 keV to be present in the core, without detectable O vi emission, the O abundance of the cooling plasma would have to be unrealistically low. The lack of larger amounts of gas radiatively cooling below 0.5 keV implies the presence of heating. A similar temperature floor at ~0.5 keV is observed in the Perseus cluster, Centaurus cluster, 2A 0335+096, Abell 262, Abell 3581, and HCG 62. (Sanders & Fabian 2007; Sanders et al. 2008, 2009, 2010a).

The energy emitted per unit volume in a blob of 0.5 keV gas, that is in pressure equilibrium with the surrounding 1 keV and 2 keV gas, is 4.8 times larger than the energy emitted by the neighboring volume of gas at 1 keV and 30 times larger than for the gas at 2 keV. Therefore, any heating process preventing the coolest gas phase from cooling below the ~0.5 keV temperature floor and providing energy uniformly in a volume-averaged way would overheat the surrounding gas and is ruled out by the data. The mechanism that heats the coolest gas clearly provides more energy per unit volume to cooler, denser phases than it does to the hotter phases.

An alternative explanation is that the coolest X-ray plasma cools non-radiatively by mixing. Sanders et al. (2010a) reached similar conclusions for a sample of cool core clusters. The coldest X-ray plasma in M 87 might cool non-radiatively by mixing with the cold optical line emitting filamentary gas, allowing efficient conduction between the two phases (Fabian et al. 2002; Soker et al. 2003). As indicated by the fact that all the bright Hα+[NII] filaments end at the innermost shock front, this mixing might be promoted by the shock, which induces enhanced shear motions, and might also power the detected optical and UV line emission (see the next section).

### 4.5 The nature of the Hα filaments

The optical emission line filaments in M 87 are likely due to cooled gas, enriched by dust from stellar mass loss (Sparks et al. 1993), which has been uplifted by the buoyant relativistic plasma, together with the coolest X-ray emitting phase. The total mass of the ~10^4 K Hα emitting gas filament in the filament system in M 87 is estimated to be of the order of $10^6 M_\odot$ (Sparks et al. 1993), which is comparable to the mass of ~0.5 keV gas. However, the total mass of cold neutral and molecular gas based on the upper limits on CO emission within the bright Hα emitting regions is only a few times $10^6 M_\odot$ (Salomé & Combes 2008). This implies that the Hα emitting gas is not a thin skin on the underlying clouds of neutral and molecular gas as in the Perseus cluster, where the inferred total mass of the cold gas is as high as $4 \times 10^{10} M_\odot$ (Salomé et al. 2006). Recently, Sparks et al. (2009) discovered filaments of C iv emission in M 87, with a total power of $1.1 \times 10^{39} \text{erg s}^{-1}$, arising from gas at a temperature of ~10^9 K, which spatially coincides with the Hα filaments on all scales. This detection indicates that the cool and hot gas phases are in thermal communication. The emission strengths are consistent with thermal conduction, which would create this intermediate temperature phase at the interface of the hot ICM and the cooler gas. However, even though conduction can quantitatively provide the energy seen in the form of line emission (Sparks et al. 2004), it would have to proceed at close to the Spitzer or saturated levels to power the filaments. The very thin and long Hα filaments are magnetized (see Sect. 4.2 and Fabian et al. 2008) and the likely orientation of the magnetic fields parallel to the interface of the cold and hot phase would largely suppress the level of conduction. Thus
it seems unlikely that thermal conduction alone can explain the optical line emission.

All of the bright Hα emission in M 87 is observed in the downstream region of the innermost <3 Myr old shock front, within a radius of ∼0.6′. This suggests that the Hα emission in M 87 is somehow related to shocks in the ICM. The passage of a shock accelerates the intra-cluster medium, but because of the large density contrast the relatively cool Hα emitting gas is left behind, resulting in a sudden strong shear around the filaments. It is likely that such shear promotes mixing of the cold gas with the ambient hot ICM via instabilities. Ferland et al. (2009) recently showed that the spectra of optical filaments observed around the central galaxies of cooling core clusters can be explained if the filaments are heated by ionizing particles, either conducted from the surrounding regions or produced in situ by MHD waves. By facilitating contact between the hot thermal particles and the cold gas, mixing can supply the power and the ionizing particles needed to explain the optical line emission spectrum. Mixing of X-ray emitting plasma with the cold gas also naturally explains the presence of the ∼10^7 K intermediate temperature gas phase. If the coolest X-ray emitting gas cools by mixing with the filamentary gas behind the shock front and conductively connects with it (e.g. Begelman & Fabian 1990, Soker et al. 2004), then its thermal energy will be radiated away in the UV band, in the optical Hα+[NⅡ], and most likely at infrared wavelengths in the presence of dust.

4.6 Implications for galaxy formation models

The series of recent ‘radio’ or ‘jet’-mode AGN outbursts in M 87, revealed in exquisite detail by the Chandra data, by no means represent a unique or extreme phenomenon. For example, a complete, flux-limited study of eighteen optically and X-ray bright, nearby galaxies, including M 87, by Dunn et al. (2010) shows that 17/18 sources exhibit some form of current radio activity associated with the central AGN (see also Best et al. 2005, Dunn & Fabian 2006, Sun 2009). Allen et al. (2006) also show that the efficiency with which the accretion of hot gas powers jets in giant ellipticals, including M 87, is remarkably uniform. Our results for the nearest, brightest cluster core show that even the current, relatively modest level of radio mode AGN activity has been sufficient to remove a sizeable fraction of the coolest, lowest entropy gas from the central galaxy. This is the material that would have cooled to form stars (Peterson & Fabian 2006). Our results therefore provide direct evidence that radio mode AGN input has a profound effect on the ability of large galaxies to form stars from their surrounding X-ray emitting halos.

5 CONCLUSIONS

Using a combination of deep (574 ks) Chandra data, XMM-Newton high-resolution spectra, and optical Hα+[NⅡ] images, we have performed an in-depth study of AGN feedback in M 87. Accounting for the fact that the long X-ray and radio “arms” are seen in projection with likely angles of ∼15°–30° from our line-of-sight, we find that:

- The mass of the uplifted low entropy gas in the arms is comparable to the gas mass in the approximately spherically symmetric 3.8 kpc core, demonstrating that the AGN has a profound effect on its immediate surroundings. This result has important implications for understanding AGN feedback in galaxy formation models (e.g. Croton et al. 2006, De Lucia & Blaizot 2007, Sijacki et al. 2007).

- The coolest detected X-ray plasma, with a temperature of ∼0.5 keV, the Hα+[NⅡ] emitting gas, and the UV emitting gas are copospatial, and appear to be arranged in magnetized filaments within the hot ambient atmosphere, forming a multi-phase medium.

- We do not detect X-ray emitting gas with temperatures below ∼0.5 keV. To remain in steady state and at constant pressure, the filaments of 0.5 keV gas would require a 5 times higher heating rate than the 1 keV gas, and 30 times stronger heating than 2 keV plasma. Thus, a uniform, volume-averaged heating mechanism would overheat the surrounding gas and can be ruled out in M 87.

- All of the bright Hα and UV filaments are seen in the downstream region of the <3 Myr old shock front, within a radius of ∼0.6′. This argues that the generation of Hα and UV emission in M 87 is related to shocks in the ICM.

Based on these observations we propose that shocks induce shearing around the denser gas filaments, thereby promoting mixing of the cold gas with the ambient hot ICM via instabilities. This process may both provide a mechanism for powering the optical line emission and explain the lack of gas with temperatures under 0.5 keV:

- By helping to get hot thermal particles into contact with the cool, line-emitting gas, mixing can supply the power and the ionizing particles needed to explain the optical spectra of the Hα+[NⅡ] nebulae (see Ferland et al. 2009).

- Mixing of the coolest X-ray emitting plasma with the cold optical line emitting filamentary gas promotes efficient conduction between the two phases, allowing the X-ray gas to cool non-radiatively, which may explain the lack of gas with temperatures under 0.5 keV.

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