ACTIVE-GALACTIC-NUCLEUS-DRIVEN WEATHER AND MULTIPHASE GAS IN THE CORE OF THE NGC 5044 GALAXY GROUP

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ABSTRACT

A deep \textit{Chandra} observation of the X-ray bright group, NGC 5044, shows that the central region of this group has been strongly perturbed by repeated active galactic nucleus (AGN) outbursts. These recent AGN outbursts have produced many small X-ray cavities, cool filaments, and cold fronts. We find a correlation between the coolest X-ray emitting gas and the morphology of the H\(\alpha\) filaments. The H\(\alpha\) filaments are oriented in the direction of the X-ray cavities, suggesting that the warm gas responsible for the H\(\alpha\) emission originated near the center of NGC 5044 and was dredged up behind the buoyant, AGN-inflated X-ray cavities. A detailed spectroscopic analysis shows that the central region of NGC 5044 contains spatially varying amounts of multiphase gas. The regions with the most inhomogeneous gas temperature distribution tend to correlate with the extended 235 MHz and 610 MHz radio emission detected by the Giant Metrewave Radio Telescope. This may result from gas entrainment within the radio emitting plasma or mixing of different temperature gas in the regions surrounding the radio emitting plasma by AGN-induced turbulence. Accounting for the effects of multiphase gas, we find that the abundance of heavy elements is fairly uniform within the central 100 kpc, with abundances of 60\%–80\% solar for all elements except oxygen, which has a significantly sub-solar abundance. In the absence of continued AGN outbursts, the gas in the center of NGC 5044 should attain a more homogeneous distribution of gas temperature through the dissipation of turbulent kinetic energy and heat conduction in approximately \(10^8\) yr. The presence of multiphase gas in NGC 5044 indicates that the time between recent AGN outbursts has been less than \(\sim 10^8\) yr.

\textit{Key words:} galaxies: abundances – galaxies: active – galaxies: clusters: general – galaxies: clusters: intracluster medium – galaxies: groups: individual (NGC 5044)

\textit{Online-only material:} color figures

1. INTRODUCTION

\textit{Chandra} and \textit{XMM-Newton} observations have shown that there is a strong feedback mechanism between the central active galactic nucleus (AGN) and the energetics of the hot gas in groups and clusters of galaxies (e.g., Peterson & Fabian 2006; McNamara & Nulsen 2007). AGN outbursts in the central dominant galaxy in groups and clusters, which are themselves fueled by the accretion of cooling gas, can produce shocks, buoyant cavities, and sound waves, all of which lead to reheating of the cooling gas. This AGN-cooling flow feedback mechanism is also an important process in galaxy formation and can explain the observed correlation between bulge mass and central black hole mass (e.g., Gebhardt et al. 2000) and the cutoff in the number of massive galaxies (Croton et al. 2006).

AGN outbursts can have a much more significant impact on the energetics of the hot gas in groups compared to that in rich clusters, due to their shallower potential wells. NGC 5044 is the X-ray brightest group in the sky and was previously observed by \textit{Chandra} for 20 ks on 2000 March 19. A joint \textit{Chandra}/\textit{XMM-Newton} analysis of these observations by Buote et al. (2003) found evidence for multiphase gas within the central 30 kpc. In a further analysis of the \textit{Chandra} data, Gastaldello et al. (2009) noted the presence of two cavities in the central region of the group and a cold front toward the southeast (SE). The \textit{XMM-Newton} observation of NGC 5044 showed an additional cold front toward the northwest (NW; Buote et al. 2003). In David et al. (2009, hereafter Paper I), we presented the results of a deeper 80 ks \textit{Chandra} observation of NGC 5044 and showed that the central region of this group has been perturbed by several recent AGN outbursts and also by motion of the central galaxy relative to the surrounding intragroup gas. Giant Metrewave Radio Telescope (GMRT) observations at 235 MHz and 610 MHz show direct evidence for uplifting of low entropy gas from the center of NGC 5044 behind buoyant, AGN-inflated X-ray cavities. Most of the X-ray cavities in NGC 5044, however, remain radio quiet in our GMRT observations. The roughly isotropic distribution of the small radio quiet cavities suggests that the group weather has a significant impact on the dynamics of these bubbles as they buoyantly rise. We also showed in Paper I that the total mechanical power of the small radio quiet cavities is sufficient to suppress about one-half of the total radiative cooling within the central 10 kpc. In this paper, we discuss how AGN-driven turbulence has produced a multiphase medium in the center of NGC 5044 and how this impacts estimates of the abundance and distribution of heavy elements.

This paper is organized in the following manner. Details of the ACIS data analysis are described in Section 2. Section 3 presents temperature and abundance maps for the center of NGC 5044 and Section 4 contains a discussion about systematic effects in the derivation of elemental abundances when fitting emission from multiphase gas with non-solar abundance ratios. In Section 5, we show how abundance profiles for NGC 5044...
depend on the assumed spectral model. Section 6 presents a comparison between XMM-Newton- and Chandra-derived abundances. Correlations between the X-ray and He emission are discussed in Section 7. The implications of our results are discussed in Section 8, and Section 9 contains a brief summary of our main results.

2. DATA ANALYSIS

NGC 5044 was observed by Chandra on 2008 March 7 (ObsID 9399) for a total of 82,710 s. All data analysis was performed with CIAO 4.2 and CALDB 4.2.1. Since the X-ray emission from NGC 5044 completely fills the S3 chip, the back-side illuminated chip S1 was used to screen for background flares. Light curves were made in the 2.5–7.0 keV and 9.0–12.0 keV energy bands for the diffuse emission on S1. No background flares exceeding a count rate threshold of 20% above the quiescent background count rate were detected during the observation. Background images were generated from the standard set of blank sky images in the Chandra CALDB and the exposure times in the background images were adjusted to yield the same 9.0–12.0 keV count rates as in the NGC 5044 data (see Paper I for more details about the data analysis). The GMRT data for NGC 5044 were obtained as part of a low-frequency radio survey of elliptical-dominated galaxy groups (see Giacintucci et al. 2011; Gitti et al. 2010). Throughout this paper, we use a luminosity distance of $D_L = 38.8$ Mpc for NGC 5044, which corresponds to $1'' = 185$ pc.

3. TEMPERATURE AND ABUNDANCE MAPS

A temperature map covering the ACIS-S3 chip (approximately 90 kpc on a side) is shown in Figure 1. The temperature map was derived using the same method described in O’Sullivan et al. (2005). All spectra were fit to an absorbed apec model with the absorption fixed to the galactic value ($N_H(\text{gal}) = 4.94 \times 10^{20}$ cm$^{-2}$) and the temperature, abundance, and normalization treated as free parameters. Regions were chosen to include at least 1600 net counts. The middle panel of Figure 1 shows the best-fit temperature and the left- and right-hand panels show the 90% lower and upper limits on the temperature. The temperature map shown in Figure 1 is very similar to the temperature map presented in Paper I, which was derived from the energy centroid of the blended Fe–L lines. Figure 1 shows that there is a great deal of structure in the temperature map and that the coolest gas extends toward the SE. As discussed in Paper I, all of the bright X-ray filaments contain cooler gas compared to the surrounding regions. A more in-depth discussion of the features in the NGC 5044 temperature map is given in Paper I.

The corresponding abundance map for NGC 5044 is shown in Figure 2. All three panels in Figure 2 show the presence of cloud-like and filament-like regions of high abundance gas. There is also a large extended region of very low abundance gas in the SE corner of the S3 chip. Most of the high abundance clouds are located at larger radii than the central X-ray cavities (see Figure 3), but interior to the SE cold front noted in Paper I (see Figure 4). The high abundance filaments are primarily located at larger radii than the SE cold front. Except for the spatial coincidence between the high abundance cloud toward the NE and an X-ray bright filament, there are no significant correlations between the high abundance regions, features in the ACIS image, the unsharp masked image, or the temperature map.

As discussed in Paper I, the 235 MHz radio emission passes through the southern X-ray cavity, bends to the west just behind the SE cold front, and then undergoes another sharp bend toward the south, at the location of the SE cold front. Figure 4 shows that the 235 MHz radio emission passes through regions with the lowest abundances and threads the region between the high abundance clouds. The lowest abundance gas is located in the southwest (SW) corner of S3, at the same position as the detached 235 MHz radio lobe.

To determine the accuracy of the method used for deriving the abundances shown in Figure 2, we extracted spectra from seven regions with super solar abundances and five regions with sub-solar abundances (see Figure 5). These spectra were then fit to a single apec model in the 0.5–3.0 keV energy band with the absorption fixed at the galactic value (see the results in Table 1). These results are in good agreement with the trends seen in the abundance map and show that the abundances differ by a factor

![Figure 1. Temperature map covering the ACIS-S3 chip. The central panel shows the best-fit temperature and the left and right panels show the 90% lower and upper limits on the temperature. The spectra were fit with an absorbed apec model with the temperature, abundance, and normalization treated as free parameters and the absorption fixed at the galactic value.](Image)
of approximately three between the high and low abundance regions.

4. SYSTEMATIC EFFECTS IN MEASURING ABUNDANCES OF HEAVY ELEMENTS

Care must always be taken when estimating abundances for gas which is likely multiphase (e.g., Buote 1999; Rasia et al. 2008). In general, abundance estimates derived from fitting CCD resolution spectra of multiphase gas are highly model dependent. Abundances are usually underestimated when fitting the emission from multiphase gas with temperatures of $\sim 1$ keV with single-temperature models. The abundance map shown in Figure 2 is based on fitting the projected spectra to an absorbed $apec$ model with the absorption fixed at the galactic value. In addition to the presence of multiphase gas, the derived abundances can also be affected by unresolved low-mass X-ray binaries (LMXBs), non-solar ratios of heavy elements, and excess absorption and projection effects.

4.1. Unresolved LMXBs

In Paper I, we found that the power-law emission from unresolved LMXBs can affect the derived spectral properties in the central region of NGC 5044. We also derived the ratio between the X-ray luminosity of the LMXBs and the $K$-band luminosity of NGC 5044 in Paper I. Using this ratio, and the Two Micron All Sky Survey image of NGC 5044, we re-fit the spectra extracted from the high and low abundance regions...
Figure 4. GMRT 235 MHz contours overlayed on the abundance map (the central panel of Figure 4). The beam size is 22″ by 16″ and the lowest contour is shown at 3σ = 0.75 mJy b−1 = 0.2 mJy b−1. The white arc shows the location of the SE cold front (see Paper I).

(A color version of this figure is available in the online journal.)

shown in Figure 5 with an absorbed apec plus power-law model with the normalization of the power-law component frozen at the value derived from the K-band luminosity within each region. We found that the improvement in the quality of the fits is statistically insignificant (based on an F-test) and that there is no significant effect on the derived abundances. This is mainly due to the use of a soft energy band (0.5–3.0 keV) in our spectral analysis. Paper I showed that unresolved emission from LMXBs primarily affects the spectroscopic results when higher energy photons are included in the analysis.

4.2. Non-solar Abundance Ratios

We next fit the set of spectra to an absorbed apec model with free absorption, an absorbed vapec model with free O, Mg, Ne, Si, S, and Fe abundances (freeing up one element at a time), and an absorbed two-temperature vapec model. The single greatest improvement in the quality of the spectral fits (based on an F-test) was obtained by fitting the spectra with an absorbed vapec model with the absorption fixed at the galactic value and O and Fe allowed to vary independently. The results of this spectral analysis are shown in Table 2. This table shows that for six of the seven high abundance regions, there is a statistically significant improvement in the quality of the spectral fits. For the low abundance regions, the quality of the fits is only improved in one out of five regions. While the derived Fe abundances in the high abundance regions are still significantly greater than the Fe abundances in the low abundance regions (compare Tables 1 and 2), the ratio of the average Fe abundance between the high and low abundance regions is significantly reduced by allowing O and Fe to vary independently. Figure 6 shows that the high and low abundance regions also have different O/Fe ratios. The high abundance regions tend to have low O/Fe ratios, while the low abundance regions have O/Fe ratios mostly consistent with the solar ratio (which is why the low abundance regions are well fit with an apec model).

To demonstrate the dependence of the abundance, Z, derived from fitting an apec model to gas with a non-solar O/Fe ratio, we simulated a set of 1 keV spectra using a vapec model with a solar abundance of Fe and a range of O/Fe values. These spectra were then fit with an apec model. Figure 7 shows that the best-fit abundance derived from an apec model can be significantly overestimated when fitting the emission from gas with an intrinsically low O/Fe ratio. By excising the O emission in the spectral analysis, and only fitting the data in the 0.8–3.0 keV energy band, we find that the abundance derived from an apec model is consistent with the Fe abundance derived from a vapec model (see Table 3). Freeing up additional heavy elements in the vapec model (i.e., Mg, Ne, Si, and S) did not produce a statistically significant improvement in the spectral analysis or alter the best-fit O and Fe abundances given in Table 2.
Figure 5. High and low abundance regions used for more in-depth spectral analysis. The small heavy white circle indicates the location of the AGN at the center of NGC 5044.

(A color version of this figure is available in the online journal.)

Figure 6. Scatter plot of the O/Fe ratios and Fe abundances for the high abundance clouds (black) and low abundance regions (red) derived from fitting the spectra to a single-temperature vapec model. All error bars are shown at 1σ.

(A color version of this figure is available in the online journal.)

4.3. Excess Absorption

It is possible that the low O/Fe ratios derived in the high abundance regions are due to excess absorption which would preferentially absorb the O emission lines. We therefore generated a set of simulated vapec spectra with solar O/Fe ratios and a range of excess absorption. These spectra were then fit to a vapec model with the O and Fe abundances treated as free parameters and the absorption fixed at the galactic value. The sensitivity of the derived O/Fe ratio as a function of excess absorption is shown in Figure 8. This figure shows that at least $5 \times 10^{20}$ cm$^{-2}$ of excess absorption is required to produce the low O/Fe ratios observed in the high abundance regions. Table 4 shows the results of fitting the sample spectra to a vapec model with $N_H$ and the O and Fe abundances treated as free parameters. Based on an $F$-test, there is very little statistical improvement in...
the quality of the fits compared to that obtained with $N_H$ fixed at the galactic value. In addition, only 2 of the 12 regions have a best-fit excess $N_H$ of more than $1.0 \times 10^{20}$ cm$^{-2}$ at the 90% confidence limit. There is also no correlation between the O/Fe ratio and the best-fit excess $N_H$ among these regions.

The low-energy quantum efficiency (QE) of the ACIS detectors has continued to decrease during the course of the Chandra mission due to outgassed material condensing on the cold ACIS filters. Our analysis uses the latest update to the ACIS contamination model which was released in CALDB 4.2 on 2009 December 15; however, systematic uncertainties in the ACIS contamination model could affect our derived O abundances. In addition to the energy dependence of the absorbing material, the ACIS-S contamination model also includes a time dependence and a dependence on chipy (parallel to the read-out direction). To estimate the systematic uncertainty in the CALDB 4.2 version of the ACIS contamination model, we extracted a spectrum from the 2009 observation of the Coma Cluster (which has a very low galactic column density of $N_H = 5.5 \times 10^{19}$) spanning the same range in chipy as that covered by the high abundance clouds in the NGC 5044 observation. The spectrum was then fit to an absorbed apec model with the absorption frozen at the galactic value. See the notes to Table 1 for further details.

4.4. Multiphase Gas

Table 5 shows the results of fitting the spectra to a two-temperature apec model with the O and Fe abundances linked between the two temperature components and the absorption fixed at the galactic value. For regions H1, H7, and L5, the two temperature fits were essentially degenerate with respect to the single-temperature fits (i.e., the values for the two temperatures overlap within their uncertainties). For these

![Figure 8. Best-fit O/Fe ratios derived from fitting an absorbed apec model with the absorption frozen at the galactic value to simulated spectra generated from a vapec model with a solar O/Fe ratio and a range of excess absorption ($\Delta N_H$).](image)

### Table 2

| Region | $kT$ (keV) | $Z$ (Solar) | $\chi^2$ | dof | F-test Prob. |
|--------|------------|-------------|---------|-----|--------------|
| H1     | 1.00 (0.99–1.01) | 0.92 (0.81–1.04) | 0.29 (0.11–0.50) | 96.4 | 89 | $7.2 \times 10^{-4}$ |
| H2     | 0.91 (0.90–0.92) | 0.70 (0.66–0.74) | 0.00 (< 0.05) | 129.8 | 102 | $2.5 \times 10^{-11}$ |
| H3     | 0.80 (0.79–0.82) | 0.69 (0.65–0.74) | 0.08 (0.03–0.16) | 188.9 | 117 | $8.3 \times 10^{-12}$ |
| H4     | 0.88 (0.86–0.89) | 0.73 (0.64–0.87) | 0.03 (< 0.23) | 76.4 | 70 | $1.2 \times 10^{-4}$ |
| H5     | 0.78 (0.77–0.79) | 0.72 (0.67–0.81) | 0.10 (0.03–0.22) | 112.6 | 99 | $8.9 \times 10^{-9}$ |
| H6     | 0.77 (0.76–0.78) | 0.95 (0.81–1.13) | 0.34 (0.17–0.57) | 91.0 | 73 | $1.3 \times 10^{-3}$ |
| H7     | 0.93 (0.91–0.94) | 1.08 (0.92–1.32) | 0.89 (0.52–1.43) | 70.8 | 63 | 0.61 |

**Notes.** All spectra were fit in the 0.5–3.0 keV energy band to a phabs*vapec XSPEC spectral model with the absorption frozen at the galactic value and the O and Fe abundances treated as free parameters. See the notes to Table 1 for further details.

### Table 3

| Region | $kT$ (keV) | $Z$ (Solar) | $\chi^2$ | dof | F-test Prob. |
|--------|------------|-------------|---------|-----|--------------|
| H1     | 1.01 (1.00–1.02) | 1.04 (0.91–1.32) | 84.8 | 73 | - |
| H2     | 0.91 (0.90–0.93) | 0.70 (0.62–0.80) | 94.3 | 83 | - |
| H3     | 0.80 (0.79–0.81) | 0.63 (0.58–0.69) | 154.9 | 98 | - |
| H4     | 0.88 (0.87–0.89) | 0.73 (0.58–0.93) | 48.5 | 59 | - |
| H5     | 0.78 (0.77–0.79) | 0.73 (0.65–0.85) | 91.1 | 80 | - |
| H6     | 0.76 (0.75–0.77) | 0.97 (0.82–1.41) | 70.6 | 59 | - |
| H7     | 0.93 (0.92–0.94) | 1.17 (0.89–1.62) | 58.6 | 52 | - |

**Notes.** All spectra were fit in the 0.8–3.0 keV energy band to a phabs*apec XSPEC spectral model with the absorption frozen at the galactic value. See the notes to Table 1 for further details.
regions, we replicate the results from the single-temperature analysis in Table 5. A comparison of the $\chi^2$ values in Tables 2 and 5 shows that there is a significant improvement in the quality of the spectral fits for seven of the nine remaining spectra with the addition of a second temperature component. One obvious difference between the low and high abundance components is the fraction of the total flux from the cooler component. In the high abundance regions, the cooler component accounts for approximately 80% of the total flux, while in the low abundance regions, the flux from the cool and hot components is more evenly distributed.

Due to the complexity in the abundance map, we cannot perform a simple deprojection analysis. Since we are fitting projected spectra, some of the improvement obtained by fitting a two-temperature model to the spectra probably arises from the range in gas temperatures along the line of sight. Using the deprojected temperature and density profiles for NGC 5044, we calculated the flux arising from gas at different temperatures. Figure 9 shows the cumulative fraction of the 0.5–3.0 keV flux, relative to the total flux, arising from gas cooler than a given temperature along three different projected distances ($b = 10$, 20, and 30 kpc) from the center of NGC 5044. Most of the spectral extraction regions shown in Figure 5 are located approximately 20 kpc from the center of NGC 5044. Figure 9 shows that for a projected distance of $b = 20$ kpc, approximately 20% of the emission should arise from gas hotter than 1 keV due to projection effects. This is in good agreement with the $F_{c}/F_{tot}$ ratios for the high abundance regions (see Table 5), indicating that the emission from within the high abundance regions themselves is nearly single phased. The greater fraction of emission from hotter gas in the low abundance regions indicates that the gas within these regions has a greater predominance of multiphase gas.

The resulting O/Fe ratios and Fe abundances from a two-temperature spectral analysis are shown in Figure 10. Fitting the spectra to two-temperature models lessens the Fe abundance contrast between the regions initially identified as having high and low abundances based on the spectral analysis with an apec model. From Table 1, the ratio of the average abundance in the high abundance regions to the average abundance in the low abundance regions is 2.5. Fitting the spectra with a vapec model with Fe and O treated as free parameters gives an average Fe abundance ratio between the high and low abundance regions of 1.6 (see Table 2). The average Fe abundance contrast between

| Region | $kT_c$ (keV) | $kT_h$ (keV) | Fe (Solar) | O (Solar) | $N_H$ ($10^{20}$ cm$^{-2}$) | $\chi^2$ | dof | F-test Prob. |
|--------|--------------|--------------|------------|-----------|----------------|---------|-----|-------------|
| H1     | 1.00 (0.99–1.01) | 0.92 (0.81–1.04) | 0.27 (0.06–0.54) | 4.73 (2.98–6.54) | (1.92–7.74) | 96.4 | 88 | 1.00 |
| H2     | 0.91 (0.90–0.92) | 0.67 (0.62–0.73) | 0.00 (< 0.05) | 6.09 (5.39–7.18) | (4.10–7.94) | 129.0 | 101 | 0.43 |
| H3     | 0.79 (0.78–0.80) | 0.71 (0.66–0.76) | 0.19 (0.11–0.28) | 7.62 (6.73–8.53) | (6.17–9.12) | 179.4 | 116 | 0.010 |
| H4     | 0.84 (0.83–0.85) | 0.73 (0.62–0.88) | 0.12 (< 0.42) | 9.36 (7.19–11.7) | (5.74–13.4) | 63.3 | 69 | 3.3 × 10$^{-4}$ |
| H5     | 0.77 (0.76–0.78) | 0.76 (0.68–0.86) | 0.22 (0.09–0.37) | 7.24 (5.87–6.62) | (5.00–9.63) | 109.8 | 98 | 0.11 |
| H6     | 0.76 (0.75–0.77) | 0.98 (0.84–1.40) | 0.45 (0.24–1.07) | 7.13 (5.90–9.95) | (3.75–11.7) | 90.0 | 72 | 0.37 |
| H7     | 0.93 (0.91–0.95) | 1.07 (0.88–1.33) | 0.82 (0.41–1.47) | 4.22 (1.71–6.92) | (1.94–8.70) | 70.7 | 62 | 0.88 |

| Region | $kT_c$ (keV) | $kT_h$ (keV) | Fe (Solar) | O (Solar) | $F_c/F_{tot}$ | $\chi^2$ | dof | F-test Prob. |
|--------|--------------|--------------|------------|-----------|----------------|---------|-----|-------------|
| H1     | 1.00 (0.99–1.01) | 0.92 (0.81–1.04) | 0.27 (0.06–0.54) | 4.73 (2.98–6.54) | (1.92–7.74) | 96.4 | 88 | 1.00 |
| H2     | 0.83 (0.82–0.85) | 1.22 (1.11–1.33) | 0.87 (0.78–0.96) | 0.00 (< 0.07) | 0.75 | 115.0 | 100 |
| H3     | 0.78 (0.77–0.79) | 1.36 (1.24–1.47) | 1.00 (0.90–1.06) | 0.29 (0.21–0.34) | 0.89 | 154.9 | 115 |
| H4     | 0.80 (0.52–0.85) | 1.00 (0.90–1.08) | 0.95 (0.78–1.17) | 0.06 (< 0.27) | 0.88 | 57.7 | 68 |
| H5     | 0.77 (0.76–0.77) | 2.30 (1.76–3.23) | 1.08 (0.98–1.25) | 0.36 (0.25–0.66) | 0.93 | 100.2 | 97 |
| H6     | 0.74 (0.67–0.76) | 1.30 (0.96–1.57) | 1.51 (1.04–2.40) | 0.78 (0.49–1.29) | 0.90 | 85.1 | 71 |
| H7     | 0.93 (0.91–0.95) | 1.07 (0.88–1.33) | 0.82 (0.41–1.47) | ... | ... | ... | ... |

Notes. All spectra were fit in the 0.5–3.0 keV energy band to a $phabs*vapec$ XSPEC spectral model with free absorption. See the notes to Table 1 for further details. Both 1σ and 90% uncertainties are given for $N_H$.

Table 5

| Region | $kT_c$ (keV) | $kT_h$ (keV) | Fe (Solar) | O (Solar) | $F_c/F_{tot}$ | $\chi^2$ | dof | F-test Prob. |
|--------|--------------|--------------|------------|-----------|----------------|---------|-----|-------------|
| L1     | 0.80 (0.79–0.81) | 0.64 (0.59–0.69) | 0.37 (0.25–0.50) | 6.90 (5.80–7.97) | (5.12–8.02) | 131.2 | 107 | 0.10 |
| L2     | 1.05 (1.04–1.07) | 0.55 (0.48–0.65) | 0.46 (0.20–0.88) | 7.14 (5.04–9.60) | (3.55–11.4) | 72.7 | 72 | 0.33 |
| L3     | 0.95 (0.93–0.97) | 0.41 (0.34–0.48) | 0.54 (0.24–0.86) | 8.25 (5.88–10.6) | (3.45–8.6) | 105.3 | 76 | 0.24 |
| L4     | 1.05 (1.03–1.07) | 0.52 (0.46–0.64) | 0.72 (0.41–1.25) | 10.7 (8.53–13.2) | (6.90–15.4) | 83.3 | 82 | 0.015 |
| L5     | 1.06 (1.04–1.08) | 0.51 (0.46–0.56) | 0.35 (0.16–0.55) | 6.13 (4.60–7.68) | (3.64–7.86) | 127.8 | 104 | 0.51 |

Notes. All spectra were fit in the 0.5–3.0 keV energy band to a $phabs*vapec*vapec$ XSPEC spectral model with the absorption frozen at the galactic value. The lower best-fit temperature is given by $kT_c$ and the upper best-fit temperature is given by $kT_h$. The ratio between the fluxes in the cooler spectral component to the total flux in the 0.5–3.0 keV energy band is given by $F_c/F_{tot}$. See the notes to Table 1 for further details.
Figure 9. Cumulative fraction of the 0.5–3.0 keV X-ray flux, relative to the total flux, as a function of gas temperature along three different projected distances, \( b \), from the center of NGC 5044.

Figure 10. Scatter plot of the O/Fe ratios and Fe abundances for the high abundance clouds (black) and low abundance regions (red) derived from fitting the spectra to a two-temperature \textit{vapec} model (see Table 5). All error bars are shown at 1\( \sigma \).

(A color version of this figure is available in the online journal.)

the high and low abundance regions is further reduced to 1.3, when the spectra are analyzed with a two-temperature model (see Table 5). Tables 2 and 5 show that the primary reason for the reduction in the Fe abundance contrast is a 52\% increase in the Fe abundance in the low abundance regions compared to only a 26\% increase in the Fe abundance in the high abundance regions, when a second temperature component is added.

Even though the Fe abundance contrast between the low and high abundance regions is significantly reduced by fitting the spectra with a two-temperature model, there is still a clear separation between the high and low abundance regions in the O/Fe and Fe plane (see Figure 10). On average, the low abundance regions have higher O/Fe ratios than those derived for the high abundance regions. To investigate the dependence of the O/Fe ratio on the presence of multiphase gas, we simulated a set of two-temperature spectra and fit the spectra to a single-temperature model. All of the simulated two-temperature models have a solar O/Fe ratio, a lower temperature of 0.7 keV, an upper temperature of 1.3 keV, and a range in flux ratios between the two temperature components. The spectra were then fit to a single \textit{vapec} model with O and Fe allowed to vary independently. The results are shown in Figure 11. This figure shows that the O/Fe ratio can be overestimated by 30\%–50\%, due to the presence of multiphase gas which can explain the segregation seen in the O/Fe and Fe plane shown in Figure 10, if the gas in the low abundance region has a greater predominance of multiphase gas and the actual O/Fe ratios are similar between the different regions. These results imply that the apparently low abundance regions in the abundance map have a more inhomogeneous gas temperature distribution compared to the apparently high abundance regions, but that the actual Fe abundances and O/Fe ratios are fairly similar.

To further support the claim that the low abundance regions reside in highly multiphase gas, we fit the spectra to a three-temperature model with the temperatures fixed at 0.7, 1.0, and 1.3 keV and the O and Fe abundances linked between the different temperature components. Figure 12 shows the relative distribution of the emission measures for the three temperature components. This figure clearly shows that the low abundance regions have a broader temperature distribution of emission measures compared to that among the high abundance regions.

Through a joint radial analysis of \textit{Chandra} and \textit{XMM-Newton} data, Buote et al. (2003) showed that there was evidence for
multiphase gas within the central 30 kpc of NGC 5044. With our deeper Chandra observation, we have shown that there are significant temperature inhomogeneities in both radial and azimuthal directions out to at least 50 kpc. In summary, there are four reasons to suspect that the apec-derived abundance map shown in Figure 4 is more a map of temperature inhomogeneities rather than a true abundance map. These are (1) the higher values of $F_c/F_{\text{tot}}$ in the high abundance regions compared to the low abundance regions, (2) the narrower temperature distribution in the emission measures within the high abundance regions compared to that in the low abundance regions, (3) the greater increase in the derived Fe abundance in the low abundance regions compared to the high abundance regions when a second temperature component is added, and (4) the smaller values of the O/Fe ratio in the high abundance regions compared to that in the low abundance regions derived from a single-temperature analysis.

5. ABUNDANCE PROFILES

The model-dependent nature of derived abundances for emission from multiphase gas with non-solar abundance ratios makes it difficult to determine azimuthally averaged abundance profiles. Such information is essential for determining the masses and mass ratios of different elements and the relative enrichment from Type Ia and Type II supernovae. To study the sensitivity of derived abundance profiles on the assumed spectral model, we produced three sets of spectra (with 10,000, 20,000, and 40,000 net counts in each spectrum) extracted from concentric annuli centered on NGC 5044. Figure 13 shows the projected Fe abundance profile derived by fitting an absorbed vapec model with all the elemental abundances linked to Fe (this is equivalent to fitting the spectra to an apec model). Also shown in Figure 13 is the projected Fe abundance profile derived from a three-temperature fit ($kT = 0.7, 1.0, \text{ and } 1.3 \text{ keV}$) to the spectra from the high and low abundance regions.

(A color version of this figure is available in the online journal.)

To investigate the distribution of other elements, we also fit the sets of spectra with 20,000 and 40,000 net counts to an absorbed vapec model with O, Mg, Ne, Si, S, and Fe treated as free parameters. Figure 14 shows the projected Fe, Si, and O abundance profiles and Figure 15 shows the projected Mg and S abundance profiles. We do not show the Ne abundances due to their large uncertainties. Figures 14 and 15 show, that except for O, the other elements have essentially solar ratios. This explains why the spectral analysis of the low and high abundance regions analyzed in Section 6 did not improve significantly when elements other than O were allowed to vary independently of Fe.

The deprojected Fe, O, and Si abundance profiles derived from fitting single- and two-temperature models are shown in Figures 16 and 17. The spectra were deprojected using the XSPEC task project. These figures show that there is little difference between the projected and deprojected Fe and Si abundance profiles, since they are both essentially flat within the central 100 kpc. The O/Fe ratio is also significantly less than the solar ratio for both the single- and two-temperature deprojections.

6. COMPARISON WITH XMM-NEWTON EPIC AND RGS RESULTS

Buote et al. (2003) derived azimuthally averaged abundance profiles for NGC 5044 from a joint analysis of an earlier 20 ks Chandra observation and an XMM-Newton observation. They found significant improvements in the spectral analysis when the data were fit with two temperature or differential emission
measure models compared to single-temperature models and discussed the sensitivity of the derived abundances on the presence of multiphase gas. Most of their abundance profiles have a peak abundance between 10 and 30 kpc with lower values both interior and exterior to this region. The peak abundances in their profiles correspond to the ring of high abundance clouds seen in the abundance map (see Figure 2). The peak Fe abundances in Buote et al. are approximately 0.8 and 1.2 solar in the projected and deprojected analysis, which are in good agreement with the results presented here.
The Hα emission is primarily extended in the north–south direction. Figure 18 shows that there are many emission-line filaments extending at least 10 kpc from the nucleus. Most of the filaments extend toward the NW cavity and along the SW filament, which is located between the SW and S cavities. There is a clump of Hα emission within the NW cavity and some Hα emission in the SW cavity, but very little emission within the southern cavity. Both the NW and SW cavities are radio quiet based on our recent GMRT observations. The brightest and longest of the southern Hα filaments borders the western edge of the southern cavity. The temperature contours in Figure 18 show that there is a strong correlation between the location of the coolest X-ray emitting gas and the Hα emission. Gastaldello et al. (2009) also discussed the correlation between the Hα emission and X-ray emission in NGC 5044, however, their Hα image appears to be inverted in declination. In their paper, they state that they obtained the Hα from Macchetto et al. (1996) and Caon et al. (2000), but these images were not registered on the sky. Temi et al. (2007) reported evidence for distributed polycyclic aromatic hydrocarbon (PAH) emission with the same morphology as the southern extension of the Hα emission based on a Spitzer observation of NGC 5044.

As discussed in Paper I, the kinematics of the Hα emitting gas are inconsistent with an external origin for the gas (Caon et al. 2000) and are similar to the kinematics of the Hα filaments in NGC 1275 (Hatch et al. 2006). We also showed in Paper I that the most likely origin for the Hα emitting gas was due to cooling of the hot X-ray emitting gas since the stellar mass loss rate in NGC 5044 is more than an order magnitude less than the mass cooling rate. All of these results are consistent with a scenario in which the gas responsible for the Hα originates from cooling of the hot X-ray emitting gas within the central few kpc of NGC 5044, followed by dredge up behind AGN-inflated, buoyantly rising bubbles. The SW Hα filament is apparently being dredged up along the outer edge of the 235 MHz radio emitting plasma which threads the southern cavity (see Paper I).

8. DISCUSSION

The multiphase gas in the center of NGC 5044 is likely produced by AGN-induced stirring or turbulence. If all AGN activity were to cease, then the subsequent cascading of the turbulence to smaller scales and the eventual dissipation of the turbulent kinetic energy into heat, along with thermal conduction, will eventually produce a more homogeneous distribution of gas temperature. Turbulent kinetic energy is dissipated on approximately the eddy turnover time of the largest eddy which is given by $t_{\text{eddy}} = l/u$, where $l$ is the length scale of the largest eddy and $u$ is the corresponding turbulent velocity. The dissipation rate of turbulent kinetic energy per unit volume is given by (e.g., David & Nulsen 2008)

$$
\Gamma_{\text{diss}} = c_2 \rho g u^2 / l_{\text{eddy}} = c_2 \rho g l^2 / t_{\text{eddy}}, \tag{1}
$$

where $c_2$ is a constant of order unity and $\rho g$ is the gas density. We can estimate $t_{\text{eddy}}$ by assuming that the dissipation rate of turbulent kinetic energy locally balances radiative losses, i.e., $\Gamma_{\text{diss}} = \Delta L_{\text{bol}}$, where $\Delta L_{\text{bol}}$ is the bolometric luminosity of the gas per unit volume. Assuming the turbulence can be characterized by a local mixing length prescription, then the size of the largest eddies can be written as $l = \alpha r$, where $\alpha$ is a parameter between 0 and 1 and $r$ is the radial distance from the cluster center. Substituting these expressions into Equation (1)
and solving for \( t_{\text{eddy}} \) gives

\[ t_{\text{eddy}} = \left( \frac{c_2\alpha^2 r^2 \rho_c}{\Delta L_{\text{bol}}} \right)^{1/3}. \tag{2} \]

Adopting \( c_2 = 0.42 \) (based on the discussion in Dennis & Chandran 2005), we computed \( t_{\text{eddy}} \) as a function of radius for NGC 5044 for \( \alpha = 0.2 \) and 0.5 (see Figure 19). This figure shows that without further AGN outbursts, the kinetic energy associated with the present level of turbulence will be thermalized within approximately \( 10^8 \) yr within the central 10 kpc. The required turbulent velocity to locally balance radiative losses within the central 10 kpc is \( u \sim 20-40 \text{ km s}^{-1} \) for \( \alpha = 0.2-0.5 \), which gives a turbulent gas pressure less than 1\% of the thermal gas pressure within this region.

A cool cloud embedded in hotter gas will be heated by thermal conduction at a rate (see the discussion in Voit et al. 2008):

\[ H = 4\pi r_c^2 f_c \kappa(T) \Delta T / r_c, \tag{3} \]

where \( r_c \) is the radius of the cool cloud, \( \Delta T \) is the temperature difference between the cool cloud and the ambient medium, and \( f_c \) is a reduction factor relative to Spitzer conduction and \( \kappa(T) = 6 \times 10^{-7}T^{3/2} \text{ erg s}^{-1} \text{ K}^{-1} \text{ cm}^{-1} \). The timescale for conduction to heat the cool cloud to the ambient gas temperature at constant pressure is

\[ t_{\text{cond}} = \frac{5k\Delta T M_c}{2\mu m_p H}, \tag{4} \]

where \( M_c \) is the mass of the cool cloud. This equation can be written as

\[ t_{\text{cond}} = \frac{5k r_c^2 \rho_c}{6\mu m_p f_c \kappa(T)}, \tag{5} \]

where \( \rho_c \) is the gas density within the cool cloud. The conduction timescale as a function of radius is shown in Figure 19 assuming a 20\% difference between the gas temperature in the cool cloud and ambient medium, or equivalently, a 20\% contrast in density, assuming that the clouds are in pressure equilibrium, \( r_c = 1 \text{ kpc} \) and \( f_c = 0.1 \) or 0.3. This figure shows that \( t_{\text{cond}} \) is comparable to \( t_{\text{eddy}} \) within the central 10 kpc. The conduction timescale declines beyond the central 10 kpc due to the increasing gas temperature (see the temperature profile presented in Paper I) and the \( T^{3/2} \) factor in the heat conduction rate.

Figure 19 shows that both turbulence and heat conduction will produce a more homogeneous distribution of gas temperature within the central 10 kpc in NGC 5044 within approximately \( 10^8 \) yr in the absence of continued AGN-driven turbulence. The fact that there is multiphase gas within this region implies that the delay between recent AGN outbursts has been less than \( 10^8 \) yr.

While conduction may be efficient at re-heating small cool clouds beyond the central 10 kpc in NGC 5044 (see Figure 19), conduction has a negligible effect on preventing the bulk of the central gas in NGC 5044 from cooling. Figure 20 shows the value of \( f_c \) required for heat conduction to locally balance radiative losses. Within the central 20 kpc, where the gas is fairly isothermal, heat conduction rates in excess of the Spitzer value are required to suppress cooling. Beyond 50 kpc, near the peak in the temperature profile, heat conduction actually helps to cool the gas (negative values of \( f_c \)), since the divergence of the heat flux is positive in this region. Thus, there is only a small range in radii, between 25 and 50 kpc, where heat conduction could be important in preventing the gas from cooling.

9. SUMMARY

In Paper I, we showed that the central region of NGC 5044 has been strongly perturbed by at least three recent AGN outbursts. By combining GMRT and Chandra data, we found direct evidence for the uplifting of low entropy gas from the center of NGC 5044 by AGN-inflated, radio emitting X-ray cavities. The nearly continuous production of AGN-inflated bubbles over the past few \( 10^8 \) yr has probably produced some
gas turbulence within the central regions of NGC 5044. This AGN-driven turbulence can have a significant impact on the distribution of heavy elements and the production and longevity of multiphase gas in the center of NGC 5044.

In this paper, we have shown that fitting a single-temperature thermal plasma model with the ratios of the elemental abundances fixed at the solar values (e.g., *apec*) can produce significant artifacts in abundance maps. To investigate the origins of the artifacts in the *apec*-derived abundance map for NGC 5044, we extracted spectra from several regions with apparently high and low abundances and fit these spectra to a variety of spectral models with different combinations of free parameters. The single greatest improvement in the spectral analysis was obtained by fitting the spectra with a *vapec* model with the O and Fe abundances allowed to vary independently. For the apparently high abundance regions, the best-fit Fe abundances derived with the *vapec* model are significantly less than the abundances obtained with the *apec* model. These high abundance regions also have best-fit values of the O/Fe ratio significantly less than the solar value. For the apparently low abundance regions, the best-fit Fe abundances derived with the *vapec* model are essentially consistent with the abundances derived with the *apec* model. The low abundance regions have near solar O/Fe ratios. Freeing up the abundance of other heavy elements does not further improve the spectral fits in any of the extracted spectra, indicating that the abundance ratios of the other elements are essentially consistent with the solar ratios. This analysis showed that a substantial portion of the artifacts in the *apec*-derived abundance map is due to the enforcement of a solar O/Fe ratio in the spectral analysis. This result was confirmed by generating a set of simulated *vapec* spectra with a range of O/Fe values and fitting the data to an *apec* model. We found that the best-fit abundance obtained with an *apec* model increases with a decreasing O/Fe ratio.

After allowing for non-solar O/Fe values in the spectral analysis, the next greatest single improvement in the quality of the spectral fits was obtained by including a second temperature component. The addition of a second temperature component produces a slight increase in the Fe abundance in the apparently high abundance regions and a much greater increase in the Fe abundance in the apparently low abundance regions. The O/Fe ratios are consistent between the single- and two-temperature spectral analysis, given the uncertainties. The flux from the second temperature component in the apparently high abundance regions is consistent with that expected from projection effects given the deprojected temperature profile of NGC 5044. For the spectra extracted from the regions with apparently low abundances, the emission from the two different temperature components is more evenly distributed. In addition to fitting the spectra to a two-temperature model, we also fit the spectra to a three-temperature model with the temperatures fixed at 0.7, 1.0, and 1.3 keV. This analysis showed that the emission from the apparently low abundance regions is more evenly distributed among the different temperature components compared to the emission from the apparently high abundance regions, confirming that inhomogeneities in the temperature distribution are partly responsible for producing the artifacts in the *apec*-derived abundance map. We also found that excess absorption and emission from unresolved LMXBs cannot produce the artifacts observed in the *apec*-derived abundance map.

We have shown that deprojected abundance profiles are very sensitive to the assumed spectral model. A single-temperature *apec* model produces a deprojected abundance profile for NGC 5044 that increases by a factor of approximately two from 100 to 10 kpc and then decreases inward. By fitting the same set of spectra with a *vapec* model with the O and Fe abundances allowed to vary independently, we obtain deprojected O and Fe abundance profiles that are fairly uniform within the central 100 kpc. Central dips in abundance profiles are a fairly common occurrence in cooling flow clusters (e.g., Sanders et al. 2004; Churazov et al. 2004). Our results show that such dips in the central abundance profile could be due to non-solar ratios of the heavy elements or the presence of multiphase gas. Excluding oxygen, all of the other elements that produce strong emission lines in 1 keV gas (i.e., Mg, Si, and S) have essentially flat abundance profiles with near solar ratios within the central 100 kpc.

The O/Fe ratio is a useful diagnostic for determining the relative enrichment from Type Ia and Type II supernovae. However, estimates of the O/Fe ratio are very sensitive to the presence of multiphase gas. By generating a set of simulated spectra, we have shown that the O/Fe ratio can be overestimated by factors of two to three when the emission from multiphase gas is fit with a single-temperature model. While the uncertainties on the O/Fe ratios obtained from our spectral analysis are fairly large when more than one temperature component is included in the spectral analysis, on average, we find significantly sub-solar values of O/Fe within the central 100 kpc of NGC 5044. This implies a greater relative enrichment from Type Ia enrichment compared to solar abundance gas which is consistent with previous studies of the central regions in groups and clusters (e.g., Finoguenov et al. 2000, 2001).

The multiphase gas in NGC 5044 is probably produced by AGN-induced turbulence. We have shown that without further AGN outbursts, the gas in the center of NGC 5044 should acquire a more homogeneous distribution of temperature within 10^5 yr due to the dissipation of turbulent kinetic energy and the effects of thermal conduction. The fact that there is a significant component of multiphase gas in the center of NGC 5044 shows that the delay between successive AGN outbursts must be less than 10^8 yr. We have recently obtained deeper GMRT data for NGC 5044 to better probe the past AGN history in this system and we will present the results in a subsequent paper.

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