1. INTRODUCTION

Galaxy clusters are filled with an intracluster medium (ICM) of hot, X-ray emitting gas. X-ray observations of this gas have shown that it can have significant substructure, even in seemingly relaxed clusters. This substructure is sometimes related to the merger history of the cluster.

Some of the most obvious features are cold fronts, which appear as surface brightness discontinuities across which the density and temperature sharply change while the pressure does not (Markevitch & Vikhlinin 2007). Spiral features, which are directly related to cold fronts, have been observed in clusters such as Perseus (Churazov et al. 2003; Fabian et al. 2006), Virgo (Simionescu et al. 2010), and A496 (Roediger et al. 2012b), as well as many others (Laganá et al. 2010). The radial extents of these spirals range from less than 50 kpc for the Centaurus cluster to approximately 245 kpc for A85. The spiral in A496 extends out to approximately 150 kpc (Roediger et al. 2012b), while the Virgo cluster shows a cold front feature out to 90 kpc (Simionescu et al. 2010). The spiral in the Perseus cluster extends to about 150 kpc (Churazov et al. 2003). Simionescu et al. (2012) found evidence that the spiral in Perseus may extend to 700 kpc in the east and over a Mpc in the west; however, these cold fronts do not connect to form a continuous spiral despite the very deep available observations.

Cold fronts and spirals are created by mergers, which displace the cool, dense cluster gas from the center of the potential well. These features have also been seen in simulations (Ascasibar & Markevitch 2006; ZuHone et al. 2010, 2011), which show that a spiral can be created by an off-center minor merger with a subcluster. These simulations are idealized binary mergers. Ascasibar & Markevitch (2006) show explicitly that sloshing gas can create cold fronts and they are a consequence of minor mergers, while the ZuHone et al. (2010, 2011) simulations explore the effects of magnetized gas and viscosity on the properties of the spiral. Roediger et al. (2011, 2012b) perform simulations of Virgo and A496 to directly compare simulations to observations. The simulations of A496 explore sloshing in an elliptical cluster, which is pertinent to A2029. Since the initial fly-by in these simulations is off-center, the cool gas in the cluster acquires angular momentum and does not fall back into the cluster center radially. The cold fronts created by this sloshing are not concentric and combine to form a spiral feature. These features can persist for billions of years (Ascasibar & Markevitch 2006), and are thus not necessarily related to recent mergers. The substructure can provide clues to the merger history of the cluster, providing insight into cluster formation. Minor merger events such as those that cause cold fronts are estimated to occur at a rate of \(~1/3\) event per halo per Gyr (Ghizzardi et al. 2010).

Sloshing morphology is an unambiguous indicator of gas sloshing. Cold fronts can be caused by mergers or sloshing, which can lead to confusion as to the origin of the observed features, as in Abell 3667 (Owers et al. 2009). The orientation of the subcluster orbit can be constrained by knowing the orientation of the full extent of the spiral and the orientation of the brightness asymmetries induced by the sloshing (Roediger et al. 2012b). On large scales, extended spirals provide a mechanism for transporting metals from the center of the cluster to the outskirts. This has been seen observationally in Virgo (Simionescu et al. 2010) and A2052 (Blanton et al. 2011), and in simulations such as those in Roediger et al. (2011), although other simulations do not show signs of global broadening in the abundance distribution (Roediger et al. 2012b).

Sloshing features could also provide part of the solution for the “cooling flow” problem. In a “cooling flow” scenario, the
central region of a galaxy cluster begins to lose energy via radiation. The cooling gas contracts to maintain its pressure, which in turn causes the gas to cool even faster. In order to maintain hydrostatic equilibrium, gas continues to flow in (for a review, see Fabian 1994). With such large amounts of gas being deposited in the center of the cluster, one would expect to see significant star formation, absent a significant heating mechanism. X-ray observations of such clusters show that while there is some gas cooling to low temperatures and star formation is seen, the majority of the gas only drops to approximately 1/2 to 1/3 of the ambient temperature (Peterson et al. 2003), rather than cooling all the way to very low temperatures, and thus a heating mechanism is necessary. Clusters with strong cooling flows ($t_{\text{cool}} < 1 \text{ Gyr}$) are likely regulated by a feedback loop involving active galactic nuclei (AGNs; McNamara & Nulsen 2007). Secondary processes, such as sloshing, can also help counteract radiative losses when not enough energy is provided by the AGN (Mittal et al. 2009). Simulations show that sloshing can provide a non-negligible amount of heat to the cluster core, making it a viable additional heating mechanism (ZuHone et al. 2010). The simulations done by Keshet (2012) show that properties of cool core clusters can be explained by the presence of a sloshing spiral, and that all such clusters may contain one.

In addition to potentially resolving the “cooling flow” problem, understanding the substructure in the X-ray gas is important for cosmological studies. Since clusters are the largest gravitationally bound structures in the universe, they are a good testbed for cosmological parameters as well as the distribution of dark matter. Determining these parameters requires accurate knowledge of the mass of the cluster. Currently, the best estimates for cluster masses come from X-ray data (Markevitch & Vikhlinin 2007). For X-ray mass estimates to be reliable, we must understand in detail the processes occurring in the ICM. These mass estimates are derived under the assumption that clusters are in hydrostatic equilibrium, but mergers and feedback from AGN can cause departures from the ideal. Mergers can cause the value of $\sigma_T$ to be overestimated by about 20% (Randall et al. 2002), and AGN feedback also needs to be taken into account when calculating the masses (Battaglia et al. 2012).

Abell 2029 is a relaxed galaxy cluster at a redshift of $z = 0.0767$. It is a Bautz–Morgan type I cluster of galaxies (Abell et al. 1989). Using previous Chandra observations, Clarke et al. (2004a) report a spiral excess in A2029 out to $\sim 150 \text{ kpc}$. Early observations of A2029 using the Einstein X-Ray Observatory and ROSAT found a mass deposition rate for the cooling flow of $M$ between $\sim 350$ and $\sim 550 \, M_\odot \text{ yr}^{-1}$ (Sarazin et al. 1992; Fabian 1994; Peres et al. 1998), while Clarke et al. (2004a) found $M = 56^{+12}_{-11} \, M_\odot \text{ yr}^{-1}$ using a short Chandra observation. Optical observations show that A2029 does not have any indication of [OIII] in its spectrum, which is usually associated with a cooling flow (McNamara & Nulsen 2007).

A2029 is host to the radio source PKS1508+059. The source has the morphology of a C-shaped wide-angle tail (WAT) radio source. It was originally postulated that WAT shapes were created by a host galaxy’s motion through the ICM (Owen & Rudnick 1976); however later simulations found that the low peculiar velocities of the galaxies combined with the assumed densities and velocities of the particles within the tails themselves were not enough to produce the WAT morphology (O’Donoghue et al. 1993). With this scenario no longer a viable mechanism, it was proposed that cluster mergers could provide the ram pressure necessary to cause the observed morphology. In the cluster merger scenario, the relative velocities between merging clusters can exceed 1000 km s$^{-1}$, which would provide the necessary relative velocity to cause the bending. Observations of some systems showed that WATs were strongly correlated with X-ray substructure, which is indicative of a cluster merger (Burns et al. 1994), and simulations also showed that the morphology could be created during cluster mergers (Roettiger et al. 1996). Newer models argue that the bending can occur with lower relative velocities that are consistent with galaxies moving through a cluster ($\sim 100$–300 km s$^{-1}$) when the jets have a high flow velocity and low density (Jetha et al. 2006). It is also possible that gas sloshing could create the WAT morphology. This has been seen in simulations, even in cases where the gas velocities are not very high (Mendygral et al. 2012).

Throughout this paper, we assume a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.7$, and $\Omega_\Lambda = 0.3$. At the redshift of A2029 ($z = 0.0767$), this gives a scale of $1'' = 1.453 \text{ kpc}$ and a luminosity distance $D_L = 347.5 \text{ Mpc}$. Unless otherwise stated, errors are reported at the 90\% confidence level.

2. OBSERVATIONS

We used two Chandra pointings totaling 97.7 ks: 19.8 ks from 2000 April 12 (ObsID 891) and 77.9 ks from 2004 January 8 (ObsID 4977). Both observations were taken in faint (F) mode using the ACIS-S configuration. The cluster center is located on the S3 chip.

The data were reprocessed using CIAO version 4.4 and CALDB version 4.4.7. After the data were reprocessed using chandra_repro to create new events files, they were then filtered for flares, and background data sets were created using the blank sky background fields reprojected to match the observations. The S1 CCD chip was used for background flare filtering, as the emission from the cluster takes up the majority of the S3 chip. To remove the flares, no time was removed from the 19.8 ks exposure, while the longer exposure was filtered from 77.9 ks to 76.9 ks.

3. IMAGES

A merged, background- and exposure-corrected image of the two exposures using the energy range 0.3–10.0 keV was created, and is shown in the left panel of Figure 1. It has been smoothed with a 1.5 Gaussian. We restrict our analysis to the S3 chip, which contains the majority of the cluster emission. The extended cluster emission is visible, as well as several point sources. The cluster emission shows very little substructure, consistent with A2029 being a relaxed cluster. It is elongated along the southwest–northeast axis. There is a brightness edge just to the east/northeast of the cluster core, and a second one to the west. These can be seen in the right panel of Figure 1, and in the unsharp-masked image described in Section 3.1.2. In all of the images presented (except the spectral maps) one pixel is equal to 0.492.

Background corrections were made using the blank sky background fields. For each of the datasets, a reprojected background events file was created, and a background image was created in the 0.3–10 keV range. The background images

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4 http://cxc.harvard.edu/contrib/maxim/acisbg/COOKBOOK
Figure 1. The left panel shows a merged, background-subtracted, and exposure-map-corrected *Chandra* 96.7 ks image of A2029 (S3 chip only) in the 0.3–10 keV energy band. The image has been smoothed with a 1.′′5 Gaussian. Here we emphasize the extended emission of the cluster, which is elongated along the axis from the southwest to the northeast. The linear negative east–west feature (inside the blue box) to the south of the cluster core at α = 15h10m54.′′6 and δ = +05◦43′13′′ is the absorption shadow of an edge-on foreground spiral galaxy (Clarke et al. 2004b). The right panel shows the central 4.′5 × 4.′5 of the cluster core in the 0.3–10 keV energy band. No smoothing has been applied. The arrows highlight the X-ray surface brightness edges to the east/northeast and the west.

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

Figure 2. SDSS r-band image of A2029. The field of view matches that of Figure 1. The X-ray point sources found by wavdetect are in red, while the radio contours of the central AGN are in green. The foreground, edge-on spiral galaxy (inside the blue box) that is seen as a shadow in the cluster emission can be seen in the optical image 1.′4 south of the cD galaxy.

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

3.1. Residual Images

We used two different techniques—unsharp masking and beta-model subtraction—to enhance the features in the X-ray image, especially the spiral excess.

Before making the residual images of the extended, diffuse emission, point sources needed to be detected and removed. Point sources were detected using the CIAO wavelet detection tool wavdetect. Wavelet scales of 1, 2, 4, 8, and 16 pixels were used, and the significance threshold was set to 10−6. The point sources were detected using an unbinned, unsmoothed image (one pixel is equal to 0.′′492) for the individual datasets and then merged. Where there was overlap, the source detection from the ∼80 ks image was used. We visually examined the detected sources and removed those that were likely to be structure in the diffuse gas from the point source list. There were 34 sources in total. In Figure 2, an optical r-band image from the Sloan Digital Sky Survey (SDSS) is shown and is matched to the field-of-view of the *Chandra* image in Figure 1. The sources are marked with red circles.

Figure 2 also has radio contours displayed to show the central WAT source. The contours are taken from the Very Large Array (VLA) Faint Images of the Radio Sky at Twenty-cm (FIRST) survey (Becker et al. 1995). These contours are used throughout this paper. Note that the central AGN was not detected as an X-ray point source. It is likely that the thermal component of the gas from the cool core dominates in this region. This is discussed further in Section 4.1.

3.1.1. Unsharp Masking

We created an unsharp-masked image in the 0.3–10.0 keV energy range to enhance faint structure in the diffuse emission.

were scaled by object exposure time as well as by the ratio of count rates of the S3 chip in the 10–12 keV range after point sources were removed. The exposure maps for each observation were normalized before being merged.
sources were removed using the tool dmfilth, which replaces pixel values in the region of interest with values interpolated from surrounding regions. A point-source-free, summed image was created using the two different smoothing scales. A difference image was then created by subtracting the 9.8 Gaussian-smoothed source-free image from a 0.98 Gaussian-smoothed image that still had the point sources. The difference image was then divided by the summed image to create the unsharp-masked image.

Figure 3 shows the unsharp-masked image with radio contours overlaid (taken from the VLA FIRST survey) of the central AGN superimposed. Unsharp masking reveals the inner region of the spiral as an increase in surface brightness to the north of the cluster center. There is also a clear decrease in surface brightness to the west of the cluster core, and the northern lobe of the AGN extends into that deficit. A small surface brightness deficit can also be seen under the southern radio lobe, indicative of a bubble. This was also seen in Clarke et al. (2004a) at the 4σ level. There is a conspicuous surface brightness excess extending from the cluster core between the lobes of the AGN, which corresponds to the very inner edge of the spiral. Measuring to the very outer southeast edge, the spiral stretches to 400 kpc. This is the largest continuous sloshing spiral observed to date. Figure 5 shows the central 3′ × 3′ region of the residual image smoothed with a Gaussian kernel of 2″. Here we can more clearly see the interaction of the sloshing gas with the radio galaxy. The gas seems to flow along the direction of the spiral, which is predicted by the simulations of Ascasibar & Markevitch (2006), causing an asymmetry in the shape of the radio lobes. The southern lobe is curved in the direction of the gas flow while the northern lobe is fairly straight.

4. SPECTRAL ANALYSIS

4.1. Total Spectrum

The goal of this section is to determine the global properties of the cluster out to a large radius. We use a radius of 116″ (167 kpc), which is the cooling radius found by Sarazin et al. (1992) using the ROSAT HRI instrument and the radius used for the spectral fits in Clarke et al. (2004a). The analysis model was fitted in Sherpa using Cash statistics, and corrections were made for exposure, using the merged exposure map. A constant background of 0.07 counts pixel⁻¹ was also included, as determined from the merged background image. The best-fitting ellipticity of the emission is 0.25 ± 0.0012. The position angle of the semimajor axis of the emission is 21°2 ± 0.2°, measured from north toward east. These values are consistent with the values found by Clarke et al. (2004a). The core radius is 27.53 ± 0.2° (40 ± 0.29 kpc), with a beta index of 0.50 ± 0.0005. Errors reported are one-sigma.

The residual image, smoothed with a 7′.5 Gaussian, is shown in Figure 4, with the 1.4 GHz radio contours overlaid. The spiral excess is clearly visible, and is brightest to the north/northeast of the cluster center. The spiral extends out to ∼300 kpc from the cluster center as measured from the core to the brightest northern edge of the spiral. Measuring to the very outer southeast edge, the spiral stretches to 400 kpc. This is the largest continuous sloshing spiral observed to date. Figure 5 shows the central 3′ × 3′ region of the residual image smoothed with a Gaussian kernel of 2″. Here we can more clearly see the interaction of the sloshing gas with the radio galaxy. The gas seems to flow along the direction of the spiral, which is predicted by the simulations of Ascasibar & Markevitch (2006), causing an asymmetry in the shape of the radio lobes. The southern lobe is curved in the direction of the gas flow while the northern lobe is fairly straight.
were to be subtracted. The spectra were binned with a minimum
created for the data, but not for the background files, since those
observation individually, as well as from the events files for
specextract
was performed with point sources excluded. The CIAO tool
apsecextract was used to extract the spectra from each
observation individually, as well as from the events files for
the associated background files. Weighted response files were
created for the data, but not for the background files, since those
were to be subtracted. The spectra were binned with a minimum
of 40 counts bin⁻¹.

The spectra from the different observations were fitted simulta-
neously using the XSPEC software package, version 12.7.0
(Arnaud 1996). The fitting was done using the energy range
0.6–7.0 keV. A systematic error of 2% was applied and the blank-
sky background files were scaled so that the 10–12 keV count
rate matched that of the observations. We explored three differ-
ent models—a single temperature thermal plasma APEC model,
a model with two APEC components, and a model with an APEC
component plus a cooling flow model (MKCFLOW). For each
model, we fitted the spectra letting the absorption be both fixed
and free. In the models where the absorption was fixed, it was
held at the Galactic value of $3.14 \times 10^{20}$ cm⁻² (Dickey &
Lockman 1990). With the cooling flow model, we also ex-
plored fixing the lower temperature component to $kT_{\text{low}} =
0.0808$ keV—the lower limit of the model. Results of the spec-
tral fitting are shown in Table 1. The upper and lower error
values are the 90% confidence intervals.

We initially fitted the central region using a single tempera-
ture APEC model. This yielded a temperature of $7.54 \pm 0.09$ keV,
which is just outside the range obtained by Clarke et al. (2004a)
using a single temperature MEKAL model ($7.27^{+0.16}_{-0.14}$ keV).
Both the APEC model and the MEKAL model are collisional
plasma models. The main difference between the two models
is that the way that they handle the Fe L line. The APEC model
also adds additional spectral lines to calculate the emission
from an optically thin, thermal plasma. Whereas the MEKAL
model uses bundles of closely-spaced emission lines, the APEC
model calculates each line individually. The APEC model
also includes more recently updated radiative transition rates
and electron collisional excitation rate coefficients. The single
APEC model yielded an abundance of $0.49 \pm 0.02$ $Z_{\odot}$. Letting
the absorption vary did not change the results of the spectral fit
significantly, and yielded a high $F$-test probability. This indicates
that letting the absorption be a free parameter does not improve
the fit. For both fixed and free absorption, $\chi^2$/dof = 0.97.
Leaving the absorption as a free parameter yielded $N_H =
3.32 \pm 0.23 \times 10^{20}$ cm⁻², which is consistent with the Galactic
value from Dickey & Lockman (1990).

Adding a second APEC component to the model improved the
spectral fits significantly, yielding an $F$-test probability
of less than 0.02% compared to the single APEC model. In
this model, the abundances, both temperature components, and
both normalization components were tied together for the two
observations. The abundances for both APEC models were also
tied together. With this model, the $\chi^2$/dof fell to 0.95 for both
fixed and free absorption. Leaving the absorption fixed to the
Galactic value, the best-fitting high and low temperatures are
$kT_{\text{low}} = 5.97^{+0.55}_{-0.67}$ keV and $kT_{\text{high}} = 11.16^{+3.37}_{-1.63}$ keV. The APEC
normalization parameters,

$$K = \frac{10^{-14}}{4\pi D_a^2 (1+z)^2} \int n_H n_e dV,$$

for both components are similar ($K_{\text{low}} = 2.7^{+1.5}_{-0.9} \times 10^{-2}$ cm⁻⁵
and $K_{\text{high}} = 2.1^{+0.9}_{-1.3} \times 10^{-2}$ cm⁻⁵). Since $K$ is propor-
tional to the square of the density, this indicates that one tem-
perature component in not clearly dominant over the other.

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Table 1

| Model                | $N_H$ ($\times 10^{20}$ cm⁻²) | $kT_{\text{low}}$ (keV) | $kT_{\text{high}}$ (keV) | Abundance ($Z_{\odot}$) | $M$ ($M_\odot$ yr⁻¹) | $\chi^2$/dof |
|----------------------|-------------------------------|-------------------------|--------------------------|-------------------------|------------------------|--------------|
| APEC                 | (3.14)                        | ...                     | 7.54^{+0.09}_{-0.09}     | 0.49^{+0.02}_{-0.02}     | ...                    | 802/826 = 0.97 |
| APEC                 | 3.32^{+0.23}_{-0.23}          | ...                     | 7.48^{+0.12}_{-0.12}     | 0.49^{+0.02}_{-0.02}     | ...                    | 800/825 = 0.97 |
| APEC+APEC            | (3.14)                        | 5.97^{+0.56}_{-0.68}    | 11.16^{+3.37}_{-1.63}    | 0.52^{+0.03}_{-0.02}     | ...                    | 785/824 = 0.95 |
| APEC+MKCFLOW         | 3.33^{+0.23}_{-0.23}          | 5.98^{+0.69}_{-0.72}    | 11.3^{+2.6}_{-1.8}       | 0.51^{+0.03}_{-0.02}     | ...                    | 783/823 = 0.95 |
| APEC+MKCFLOW         | (3.14)                        | 4.28^{+0.74}_{-0.74}    | 9.68^{+1.45}_{-0.70}     | 0.53^{+0.03}_{-0.03}     | 710^{+274}_{-270}      | 795/824 = 0.96 |
| APEC+MKCFLOW         | 3.53^{+0.24}_{-0.24}          | 4.24^{+0.80}_{-0.67}    | 10.08^{+3.30}_{-1.12}    | 0.52^{+0.03}_{-0.03}     | 783^{+371}_{-268}      | 786/823 = 0.95 |
| APEC+MKCFLOW         | (3.14)                        | (0.0808)                | 7.54^{+0.09}_{-0.09}     | 0.49^{+0.02}_{-0.02}     | 1.43 \times 10^{-14}   | 802/825 = 0.97 |
| APEC+MKCFLOW         | 3.33^{+0.23}_{-0.23}          | (0.0808)                | 7.48^{+0.12}_{-0.12}     | 0.49^{+0.02}_{-0.02}     | 1.42 \times 10^{-14}   | 800/824 = 0.97 |

Note. Values in parentheses were held fixed during the model fitting.

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Figure 5. Residual image in the 0.3–10 keV energy band of the central $3' \times 3'$
region after the beta-model subtraction. The image has been smoothed with a
Gaussian kernel of $2'$. Contours of the 1.4 GHz radio emission are overlaid.

(A color version of this figure is available in the online journal.)
The abundance was $0.51_{-0.02}^{+0.03}Z_{⊙}$. Letting the absorption vary gives $N_H = 3.33 \pm 0.23 \times 10^{20}$ cm$^{-2}$, $kT_{\text{low}} = 5.98_{-0.72}^{+0.69}$ keV, $kT_{\text{high}} = 11.31_{-1.84}^{+26.4}$ keV, and $Z = 0.51_{-0.02}^{+0.03}Z_{⊙}$. In Clarke et al. (2004a), the two component MEKAL model yielded a high temperature of $kT_{\text{high}} \sim 7.5$ keV and a low temperature of $kT_{\text{low}} \sim 0.1$ keV within the same spatial region. Our high temperature value is closer to the temperature found by Vikhlinin et al. (2005), who also used Chandra. They find that between $\sim 100$ and 300 kpc the cluster temperature rises to $\sim 9$ keV. The region we explore extends out to approximately 170 kpc, so the area of increased temperature is included.

Because there is evidence of a cooling flow in A2029, we also fitted a model including a cooling flow component (MKCFLOW) with a single-temperature APEC model to account for gas outside the cooling region. The MKCFLOW model is based on one presented by Mushotzky & Szynkowiak (1988), who found that two isothermal plasmas did not provide a good physical model for cooling in clusters. This model assumes that the mass flow rate is consistent throughout the cooling flow. In this scenario, the high temperature ($kT_{\text{high}}$) component of the cooling flow model was tied to the temperature of the APEC model. As with the APEC+APEC model, the abundances of each dataset and each model were tied together. Keeping the absorption fixed, the MKCFLOW+APEC model gives best-fit temperatures $kT_{\text{high}} = 9.68^{+1.45}_{-0.70}$ keV and $kT_{\text{low}} = 4.28^{+0.74}_{-0.50}$ keV. The best-fit abundance is $0.53 \pm 0.03Z_{⊙}$. The cooling flow mass deposition rate is $M = 710^{+274}_{-270}M_{⊙} \text{yr}^{-1}$. Letting the absorption vary gives a column density of $N_H = 3.53 \pm 0.24 \times 10^{20}$ cm$^{-2}$, $kT_{\text{high}} = 10.08^{+0.30}_{-0.12}$ keV, $kT_{\text{low}} = 4.24^{+0.80}_{-0.67}$ keV, and an abundance of $0.52 \pm 0.03Z_{⊙}$. With the absorption free, $M = 783^{+371}_{-268}M_{⊙} \text{yr}^{-1}$. Comparing the MKCFLOW+APEC model with absorption free to a single-temperature APEC model (with absorption free and fixed) gives an $F$-test probability of $\sim 0.1\%$, which indicates that it is a significant improvement. Comparing the two MKCFLOW-APEC models (one with the absorption free and the other with the absorption fixed), an $F$-test shows that the one with the free absorption model is a significant improvement, yielding a probability value of $\sim 0.7\%$.

The high temperatures in the cooling flow model are consistent with the values from Vikhlinin et al. (2005), and the low temperature is consistent with the results from other clusters that show gas cools to about one-half to one-third of the ambient temperature (Peterson et al. 2003). We also fitted an APEC plus cooling flow model where $kT_{\text{low}}$ was fixed to $0.0088$ keV, which is the hard lower limit in XSPEC, to compare with Clarke et al. (2004a). In this model, the best-fit APEC values matched those of the corresponding (i.e., absorption fixed or free) single-temperature APEC model discussed above and seen in Table 1. With this fixed lower limit, the cooling flow rate was $\sim 10^{-14}M_{⊙} \text{yr}^{-1}$, making the MKCFLOW component negligible. From this we can infer that a significant fraction of the gas in this region is not cooling to very low temperatures.

The best-fit cooling flow rate of $M = 783^{+371}_{-268}M_{⊙} \text{yr}^{-1}$ determined here is higher than previously found values of between 350 and 550 $M_{⊙} \text{yr}^{-1}$ (Sarazin et al. 1992; Fabian 1994; Peres et al. 1998); however, there is overlap in the confidence intervals of our value and the higher previous value of $556^{+215}_{-206}M_{⊙} \text{yr}^{-1}$, found using ROSAT (Peres et al. 1998). These values are significantly higher than the rate of $56M_{⊙} \text{yr}^{-1}$ found by Clarke et al. (2004a) using the same region for spectral extraction. Clarke et al. (2004a) also find a $kT_{\text{high}}/kT_{\text{low}} > 50$, whereas we find $kT_{\text{high}}/kT_{\text{low}} \sim 2.4$, which is more in agreement with values seen in other clusters (Peterson et al. 2003). We explore this discrepancy further in Section 7.

4.2. Central Source

We would like to determine whether or not the central AGN can be detected spectrally. To do this, we extracted the spectrum of the central source using an aperture of 2′0 (2.9 kpc) centered on the coordinates of the radio galaxy core as reported by Taylor et al. (1994) ($α = 15^{h}10^{m}56.82$, $δ = +05^{\circ}44′41′′.26$, J2000). The background was determined locally from an annulus centered on the source with an inner radius of 2′0 (2.9 kpc) and an outer radius of 5′0 (7.3 kpc). There were approximately 1100 net counts in the region.

We fitted both a non-thermal power-law and a single-temperature APEC model with absorption both fixed and free to the region. Parameters from each dataset were tied together. The best-fitting photon index for the power-law model is $\Gamma = 2.01 \pm 0.09$, which is slightly higher than the photon index of $\Gamma \sim 1.7\sim 1.8$ seen in 90% of radio-loud AGN (Sambruna et al. 1999). Letting the absorption vary improves the power-law model (lowering the $\chi^2/\nu$); however, the value of $\Gamma$ rises to $\Gamma = 3.10^{+0.35}_{-0.30}$. This is well above the average range of values seen in other radio-loud galaxies. The single-temperature APEC model is a better fit to the region. The best-fit model for the central region is the single-temperature APEC model with the absorption free to vary; however it is not a significant improvement over fixed absorption as the $F$-test probability is $\sim 39\%$. The APEC model with free absorption yields an absorption of $N_H = 6.38^{+6.23}_{-5.49} \times 10^{20}$ cm$^{-2}$, a temperature of $kT = 2.47^{+0.44}_{-0.36}$ keV, and an abundance of $Z = 1.29^{+0.97}_{-0.53}Z_{⊙}$. Neither an APEC+APEC model nor an APEC+PO model was an improvement over the best-fitting single-temperature APEC model. Based on our best-fit model there is no detection of non-thermal emission from an AGN. This is consistent with Clarke et al. (2004a), who found that the best fit model was a single-temperature MEKAL model. They were unable to find good fits with a power-law component with a photon index $\Gamma < 3.4$.

4.3. X-Ray Spectral Maps

Spectral maps were created to examine the distributions of temperature, entropy, and abundance in the inner 250′ (370 kpc) region of the cluster, following the technique outlined in Randall et al. (2008, 2009). Spectra were extracted from the 0.6–7 keV energy range. For the temperature and entropy maps, we used a minimum of 3000 net counts per fit, and for the abundance map we used a minimum of 10,000 net counts per fit to improve the errors. The maps are binned such that each pixel is 10′. The radius of the extraction region for each pixel is allowed to grow until the minimum number of net counts is contained inside the extraction region. In the central region where the surface brightness is high, there is little-to-no overlap between the extraction regions. There, each 10′ pixel represents a spectral fit, while at the edge of the field the surface brightness is lower and the neighboring regions overlap significantly. As many as 15 pixels are contained in an extraction region at the edge of the field. Point sources were excluded from the spectral fits, as was the region that includes the foreground, edge-on spiral galaxy. The column density was fixed to the Galactic value of $3.14 \times 10^{21}$ cm$^{-2}$, but elemental abundance values were allowed to vary.

Figure 6 shows a temperature map of A2029 with contours of the brightest part of the spiral overlaid in black and the full extent
of the spiral overlaid in green. The spiral feature is coincident with the cooler parts of the cluster, as predicted in the sloshing model. Errors are, on average, between 10% and 15% across the map. They range from less than 10% in the center of the cluster where the count rate is highest, to approximately 25% at the outer edge of the map.

Along with cooler temperatures, we expect the region with the spiral excess to show higher abundances, since the sloshing displaces the metal-rich gas from the cluster core and brings it into contact with the more metal-poor ICM outside the cluster center. Figure 7 shows that the contours tend to trace the areas of highest abundance, most clearly in the bright, northern region. This is consistent with the idea that the higher metallicity gas in the center of the cluster is being displaced, creating the sloshing spiral. While the errors are large, the abundance map can be used as a visualization tool. The errors start at 20% at the lowest in the center of the map and reach up to 50% toward the edge of the field. Within the spiral region, the errors range from 20% to 40%.

We also construct a pseudo-entropy map. Pseudo-entropy is defined as $kT(K/A)^{-1/3}$, where $K$ is the APEC normalization, and $A$ is the on-chip area of the extraction region. Since $K \propto n_e^2$, the pseudo-entropy is proportional to $kTn_e^{-2/3}$. The combination of low temperature and high density in the spiral enhances the entropy and there is a noticeably lower entropy in the spiral region. This is seen in Figure 8, where the lowest entropy portion of the cluster follows the spiral structure. There is also an overall trend of entropy increasing away from the center of the cluster.

The spectral maps show that the distribution of temperature, abundance, and entropy are correlated with the spiral structure. We explore this structure in more detail in the following section.

5. THE SLOSHING SPIRAL FEATURE

The spiral feature visible in Figure 4 is similar in morphology to the spiral features induced by sloshing seen in simulations of cluster–cluster mergers originally described in Ascasisi-bar & Markevitch (2006), and more recently in, e.g., ZuHone et al. (2010, 2011). The simulations in ZuHone et al. (2011) included magnetic fields to stabilize the cold fronts against Kelvin–Helmoltz instabilities (KHIs), which give the appearance of ragged edges, in contrast with the smooth edges that are observed in many systems. Some systems, however, such as A496 (Roediger et al. 2012b) and the merging groups NGC 7618 and UGC12491 (Roediger et al. 2012a) do show distortions that are consistent with KHIs. The prevalence of smooth edges may be due to viewing the cold fronts in projection (Roediger et al. 2011).

In the simulated mergers, the cool, central gas in the cluster is displaced to larger radii, which is known as sloshing. The sloshing sets up cold fronts, and the spiral structure results when the merger is off-center, transferring angular momentum. We would expect the brightness excess seen in Figure 4 to also be seen as excesses in the surface brightness profile of the region including the spiral. The temperature profile of these regions should show cooler gas coincident with the regions of surface brightness excess. A list of global sloshing features (e.g., brightness edges, large-scale asymmetry, temperature and metallicity structure) can be found in Roediger et al. (2012b).

We have extracted surface brightness profiles from wedges in two directions, north (N) and southwest (SW), as shown in Figure 9. The N region includes the inner part of the spiral, while the SW region includes the outer part of the spiral. Due to the placement of the cluster on the chip, we were able to go out to a larger radius when exploring the properties of the SW region. The surface brightness profile obtained from the original merged image is shown in Figure 10(a). Many of the error bars are smaller than the symbols used. The excess in the N region is seen between $\sim 20''$ ($\sim 29$ kpc) and $\sim 80''$ ($\sim 116$ kpc), while the excess emission in the SW region extends beyond $\sim 80''$ ($\sim 116$ kpc). We examined a 2830 arcsec$^2$ circular region in the northern part of the spiral where there was a surface brightness excess.
Figure 7. Abundance map of A2029 with contours of the brightest part of the spiral overlaid in black and contours of the full extent of the spiral overlaid in green. The brightest part of the spiral appears coincident with a region of high abundance, although high abundance regions are also seen elsewhere in the cluster. Spectral fits were performed using a minimum of 10,000 net counts per region. This map has been smoothed with a Gaussian with a kernel radius of 30″. The scale bar shows abundance in units relative to the solar abundance.

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

Figure 8. Pseudo-entropy map of A2029 with contours of the brightest part of the spiral overlaid in black and contours of the full extent of the spiral overlaid in green. The scale bar is in arbitrary units. The part of the cluster with the lowest entropy is coincident with the spiral feature, and the entropy increases outward. The image has been smoothed with a Gaussian with a kernel radius of 30″.

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

excess seen in the surface brightness profile and compared it with an identical region at the same distance from the cluster center to the SW of the core where no surface brightness excess was observed. We did the same for examining the SW excess (as compared to the north) at larger radii using a 7850 arcsec$^2$ circular region. We find a 24% excess of counts in the brightest part of the spiral to the north of the cluster center compared to the same radial range in the SW, corresponding to 44σ. In the
The surface brightness is proportional to Blanton et al. (2009), Wong et al. (2008), and Kriss et al. (1983). The density was calculated by deprojecting the density, and pressure profiles overlaid on the residual image of the spiral feature. (A color version of this figure is available in the online journal.)

Figure 10(c) shows the electron number density profile of the two regions, with the annuli shown in the right panel of Figure 11. The spectra were fitted using an APEC thermal plasma model with the absorption fixed to the Galactic value. Elemental abundances were allowed to vary. The temperature profile is shown in Figure 10(b). The regions used to extract the spectra are larger than the regions used in the surface brightness profile to minimize the error bars. Each region has a minimum of 10,000 net counts. In the region to the north that corresponds to the surface brightness excess, the temperature is cooler than the SW region, where there is no surface brightness excess at those radii. This temperature relationship is inverted for the outer portion of the spiral. There the temperature in the SW region (where there is a surface brightness excess) is cooler than points at the same radii in the northern region (where the surface brightness is lower). The surface brightness excess to the north is greatest at $r \sim 40''–50'' (r \sim 58–73$ kpc), which is where we see the gas is most significantly cooler. For the southwest, the surface brightness is greatest at $r \geq 80'' (r \geq 116$ kpc), and the temperature is correspondingly cooler here than to the north. The relationship between the two regions is as expected in a sloshing model, where cool gas in the cluster core has been displaced to larger radii in a spiral distribution.

Figure 10(d) shows the pressure profile of the two regions. The same two wedges, but using fewer annuli, using the method described in Section 4. These regions are shown in the left panel of Figure 11. The spectra were fitted using an APEC thermal plasma model with the absorption fixed to the Galactic value. Elemental abundances were allowed to vary. The temperature profile is shown in Figure 10(b). The regions used to extract the spectra are larger than the regions used in the surface brightness profile to minimize the error bars. Each region has a minimum of 10,000 net counts. In the region to the north that corresponds to the surface brightness excess, the temperature is cooler than the SW region, where there is no surface brightness excess at those radii. This temperature relationship is inverted for the outer portion of the spiral. There the temperature in the SW region (where there is a surface brightness excess) is cooler than points at the same radii in the northern region (where the surface brightness is lower). The surface brightness excess to the north is greatest at $r \sim 40''–50'' (r \sim 58–73$ kpc), which is where we see the gas is most significantly cooler. For the southwest, the surface brightness is greatest at $r \geq 80'' (r \geq 116$ kpc), and the temperature is correspondingly cooler here than to the north. The relationship between the two regions is as expected in a sloshing model, where cool gas in the cluster core has been displaced to larger radii in a spiral distribution.

Figure 9. The two regions used for creating surface brightness, temperature, density, and pressure profiles overlaid on the residual image of the spiral feature. (A color version of this figure is available in the online journal.)

6. BENDING OF WAT LOBES THROUGH ICM SLOSHING

The radio galaxy at the center of the cluster is affected by the spiral feature, and vice versa. The radio galaxy appears to have inflated bubbles with its lobes, as evidenced by the way that the spiral does not smoothly connect to the center of the cluster in the south, and the deficit of X-ray emission at the position of the NW lobe. It is also likely that the spiral is affecting the shape of the radio lobes, giving them their WAT morphology. The lobe that has evacuated the cavity to the south appears to be bent more than the other lobe. This type of asymmetry was found in simulations by Mendygral et al. (2012). They performed three-dimensional magnetohydrodynamical simulations to explore the interaction between AGN and ICM “weather” such as sloshing and found that ICM flows could cause asymmetries between the AGN lobes and jets even in seemingly relaxed clusters. The motion of the ICM is most likely at an angle to the jet axis, as the AGN morphology is a cross between the two limiting cases—ICM motion aligned with the jet axis and ICM winds orthogonal to the jet axis—discussed in Mendygral et al. (2012).

We see that there is a WAT morphology, but the southern jet is more bent than the northern jet. This kind of morphology is seen in the simulations when the ICM winds are orthogonal to the jet axis. The northern jet is more elongated than the southern jet, which is seen in the simulations when the ICM winds are aligned with the jet axis. The southern lobe is bent toward the southwest. The gas is expected to flow inward along the spiral (see the velocity vectors in Ascasibar & Markevitch 2006, specifically their Figure 7), so the displacement of the lobe is consistent with the flow of gas along the portion of the spiral that runs parallel to the southern lobe. This kind of distortion can help provide information about the velocity structure of clusters where it is not possible to do direct measurements.

Using a method similar to the one described in Douglass et al. (2008, 2011), we estimate the relative velocity between the ICM and radio galaxy. If we assume pressure balance between the radio lobes and the ICM, we can equate pressure of the buoyant radio lobes to the dynamic ram pressure of the ICM as
Figure 10. Surface brightness profile (a), projected temperature profile (b), density profile (c), and pressure profile (d) using the sectors shown in Figure 9. In the N region, the surface brightness excess stretches from $\sim 20''$ ($\sim 29$ kpc) to $\sim 80''$ ($\sim 116$ kpc), while in the SW region the surface brightness excess extends past $\sim 80''$ ($\sim 116$ kpc). The inner dashed line marks the beginning of the spiral excess to the north. The outer dashed line marks the other edge of the spiral in the north and the inner edge of the spiral in the southwest. Error bars are one-sigma except in the temperature profile, where they are the 90% confidence intervals.

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

Figure 11. Annuli used for the temperature profile (shown in the left panel) and for the density and pressure profiles (right panel) shown in Figure 10.

(A color version of this figure is available in the online journal.)
it sloshes past the AGN, which gives

$$\frac{\rho_v v_r^2}{r_e} = \frac{\rho_{ICM} v_g^2}{r_e},$$  \hspace{1cm} (2)$$

where $r_r$ is the radius of the lobe, $v_r$ is the velocity of the plasma in the lobe, $\rho_v$ is the mass density of the lobe, $\rho_{ICM}$ is the density of the ICM (where $\rho_{ICM} = 1.92 n_e \mu m_p$; $\mu$ is the mean atomic mass of the cluster and is assumed to be 0.6 and $n_e$ is found from the density profile), $v_g$ is the velocity of the galaxy relative to the ICM, and $r_c$ is the radius of curvature of the source. Using the kinetic model of O’Donoghue et al. (1993), the condition used to determine the internal density required to produce the observed luminosity of the lobes is

$$L_{rad,l} = \epsilon \pi r_r^2 \rho_v v_r^3.$$  \hspace{1cm} (3)$$

This model assumes that some fraction ($\epsilon$) of the kinetic energy is converted into the observed radiation. Combining this with Equation (2), the velocity of the galaxy relative to the ICM is:

$$v_g = \left( \frac{2L_{rad,l}}{\epsilon \pi \rho_{ICM} v_r F r_r} \right)^{1/2}.$$  \hspace{1cm} (4)$$

Here, $L_{rad,l}$ is the radio luminosity of the lobe.

To determine the efficiency with which the kinetic energy of the outflow is converted into radiation, we need to determine the mechanical power and the total radio luminosity of the source ($\epsilon = L_{rad,l}/(E_{kin}/t)$). The kinetic energy of the AGN goes into evacuating cavities in the ICM and, in the case of relativistic jets, $E_{kin} = 4 PV$ (Churazov et al. 2001). Assuming that the AGN is in pressure equilibrium with the ICM, we can estimate the pressure from our pressure profile and find that at the outer edge of the southern lobe, $P = 6.4 \times 10^{-10}$ dyn cm$^{-2}$. To determine the volume, we estimate a circular radius for the southern lobe of 4.7 (6.9 kpc). To determine the power, we assume a typical AGN repetition rate of $5 \times 10^7$ yr (Birzan et al. 2004). We multiply this power by two to account for both lobes. To find the radio luminosity, we use the following equation:

$$L_{rad} = 4\pi D_L^2 S_{100} \int_{v_1}^{v_2} \left( \frac{v}{v_0} \right)^{-\alpha} dv.$$  \hspace{1cm} (5)$$

We find the total radio luminosity to be $3.8 \times 10^{42}$ erg s$^{-1}$, using a spectral index of $\alpha = 1.52$, a reference flux of 511 mJy at 1490 MHz (Taylor et al. 1994), and integrating between 10$^7$ Hz and 10$^{11}$ Hz. From this we find an efficiency of $\epsilon = 0.03$. Typical values of $\epsilon$ fall between 0.001 and 0.1 (Birzan et al. 2004). At the reference frequency, the core of the AGN is not visible and we can set $L_{rad,l} = L_{rad}$. From the density profile we find $\rho_{ICM} = 6. \times 10^{-26}$ g cm$^{-3}$. We measure $r_e = 17$ kpc and $r_c = 7$ kpc. The only unknown is $v_r$—the velocity of the plasma in the radio lobe. In well-collimated jets, flow velocities are estimated to be between 0.3$c$ and 0.7$c$ (Jetha et al. 2006). In the lobes, these velocities are less restricted, but may be between 0.05$c$ and 0.2$c$ (Douglass et al. 2008). Using those values as the lower and upper limits, we find that the relative velocity between the galaxy and the ICM (Equation (4)) is between 150 km s$^{-1}$ and 300 km s$^{-1}$, which is consistent with sloshing velocities (Mendygral et al. 2012). As mentioned previously, the lobe is being displaced along the direction of gas flow, so it is likely that the sloshing in A2029 is distorting the radio lobe.

### 7. COOLING VERSUS HEATING IN A2029

The gas cooling time can be calculated from the following equation (Sarazin 1988):

$$t_{cool} = 8.5 \times 10^{10} \text{yr} \left( \frac{n_p}{10^{-3} \text{cm}^{-3}} \right)^{-1} \left( \frac{T_g}{10^8 \text{K}} \right)^{1/2},$$  \hspace{1cm} (6)$$

where $n_p$ = 1.21$n_e$ is the proton number density and $T_g$ is the temperature of the gas. From the temperature and density profiles we find that $T_g = 6.1$ keV and $n_e = 0.043$ cm$^{-3}$ at a radius of 13.8 (20 kpc). Inside this radius we calculate a cooling time of $\sim 1.4 \times 10^9$ yr, which is much shorter than the Hubble time. This is another indicator (along with spectrally-determined high mass deposition rate) that cooling is important in the cluster. We can also calculate a mass deposition rate based on the X-ray luminosity of the gas. For steady-state, isobaric cooling,

$$L_{cool} = \frac{5}{2} \mu m_p \dot{M}.$$  \hspace{1cm} (7)$$

As above, $\mu$ is the mean atomic mass of the cluster (which we take to be $\mu = 0.6$). Inside a radius of 116"., $L_{cool} = 1.4 \times 10^{45}$ erg s$^{-1}$ (derived from the single APEC X-ray spectral fit). Setting $kT = 8.5$ keV (the temperature at $r = 116$"), we find $\dot{M} = 805 M_{\odot}$ yr$^{-1}$.

As discussed in Section 4.1, our spectroscopically derived cooling flow rate differs significantly from the value derived in Clarke et al. (2004a). We have performed a series of tests to determine the source of this discrepancy. One possibility is simply that the differences are due to using a deeper set of observations here, as well as updated calibrations. To test this we performed the spectral fits just on the 20 ks dataset, and found that mass deposition rate was $M = 378^{+53}_{-34} M_{\odot}$ yr$^{-1}$, which, because of the large error bars, is consistent with $M = 56 M_{\odot}$ yr$^{-1}$. A second possibility is that there is another minimum in the parameter space that gives the lower cooling flow rate. To test this we used both data sets. Since Clarke et al. (2004a) used the energy range 0.7–8 keV to do their spectral fits, we first tested the fit by using our data and fitting in that energy range. Again, the larger mass deposition rate was favored. We also fixed the mass deposition rate to $M = 56 M_{\odot}$ yr$^{-1}$, then compared that fit with our fit. Comparing with an F-test, the higher mass deposition rate is a better fit, with an F-test probability of 0.05%. We then looked at what happened when we fixed the upper energy to 7 keV, and varied the lower limit between 0.4 and 0.8 keV. Again, the larger mass deposition rate was favored. Lastly, we fitted the spectrum within a smaller radius. With a smaller radius we expected the mass deposition rate to be lower. We found that it is; however, it is still consistent with a mass deposition rate in the hundreds of solar masses per year, with no overlap in the error bars with the lower rate. We again fixed the mass deposition rate to the lower value, and still found that the higher value is a better fit. We conclude that the high mass deposition rate is the better fit, although it is not very well constrained. It is also likely that heating from the AGN is insufficient to offset the cooling. Sloshing may supply an additional heating mechanism.

Despite the high mass deposition rate, there is very little star formation taking place in A2029. Hicks et al. (2010) found a star formation rate of $M = 0.03–0.06 M_{\odot}$ yr$^{-1}$ using Hα emission from the central cD (McDonald et al. 2010). One possible explanation for the apparent lack of star formation
is heating by the central AGN. As above, we estimate the energy injection from the AGN as \( E = 4P/V \) and average over a typical source repetition rate of \( 5 \times 10^7 \) yr. This yields \( 1 \times 10^{42} \) erg s\(^{-1}\), which is an order of magnitude lower than necessary to offset the cooling. Thus A2029 provides a good example of a cluster where sloshing may be a significant component of heating that prevents large amounts of cooling (ZuHone et al. 2010). We can contrast A2029 with the cluster SPT-CLJ2344-4243 (\( \mathcal{Z} = 0.596 \)), which has a mass deposition rate of \( \dot{M} = 2700 \pm 700 \, M_\odot \, \text{yr}^{-1} \), but also shows a large star formation rate of \( \dot{M} = 798 \pm 42 \, M_\odot \, \text{yr}^{-1} \) (McDonald et al. 2013). The mass deposition rate was determined using the X-ray luminosity (McDonald et al. 2012), rather than spectroscopically. The cooling flow there is likely inducing the starburst, indicating that whatever feedback mechanism that is prevalent in low-redshift clusters such as A2029 is not present in the higher redshift system.

8. DISCUSSION AND CONCLUSIONS

We have presented deep Chandra observations of the cluster A2029. We examine in detail the spiral structure that is seen in the X-ray image after beta-model subtraction. This spiral is likely the result of an off-axis merger with a subcluster, as similar features are seen in simulations of such events. The presence of the spiral highlights the fact that even in very relaxed clusters sloshing spirals are possible (A2029 is considered to be one of the most relaxed clusters in the universe (Buote & Tsai 1996), and there is no optical evidence of substructure (Dressler 1981)). The brightest part of the spiral (shown in the black contours in Figures 6–8) extends approximately 300 kpc from the cluster core to the brightest edge directly south. Measured to the southeast edge, the full extent of the spiral reaches 400 kpc (green contours in Figures 6–8), making it the largest continuous sloshing spiral identified to date. There is some evidence that the spiral in Perseus extends out to 700 kpc in the east and over a Mpc in the west (Simionescu et al. 2012); however it is not continuous. This may indicate that it is observed at a less face-on orientation than the spiral in A2029.

The total cluster emission is best fitted by either an APEC+APEC model or an MKCFLOW+APEC model with absorption allowed to vary. The APEC+APEC model with absorption fixed gives \( kT_{\text{low}} = 5.97^{+0.96}_{-0.68} \) keV and \( kT_{\text{high}} = 11.16^{+3.7}_{-1.63} \) keV, with normalization values that are within a factor of two. The abundance for this model is \( Z = 0.52^{+0.03}_{-0.02} \) Z\(_\odot\). The cooling flow model yields a high temperature component of \( kT_{\text{high}} = 10.08^{+2.30}_{-1.12} \) keV cooling to a temperature of \( kT_{\text{low}} = 4.24^{+0.80}_{-0.67} \) keV with a mass deposition rate of \( \dot{M} = 783_{-268}^{+371} \, M_\odot \, \text{yr}^{-1} \). The abundance is \( 0.52 \pm 0.03 \) Z\(_\odot\). While fairly high, this mass deposition rate is consistent with other studies of this cluster, particularly the ROSAT value of \( 556^{+215}_{-93} \, M_\odot \, \text{yr}^{-1} \) (Peres et al. 1998). The ratio \( kT_{\text{high}}/kT_{\text{low}} \sim 2.4 \) is consistent with previous values of other clusters (Peterson et al. 2003). The mass deposition rate found here differs significantly from the rate of \( 56 \, M_\odot \, \text{yr}^{-1} \) and the ratio \( kT_{\text{high}}/kT_{\text{low}} > 50 \) found by Clarke et al. (2004a). A series of tests shows that the high mass deposition rate of \( \dot{M} = 783_{-268}^{+371} \, M_\odot \, \text{yr}^{-1} \) is a better fit to the data.

We also find that the center of the cluster is most likely dominated by the thermal component of the gas and do not find evidence for non-thermal emission from the AGN.

The surface brightness profile shows a clear brightness excess in the regions where the spiral is seen. We also see a decrease in temperature in the area of the spiral compared to the average cluster temperature, and an increase in density. Both of these are consistent with simulations of sloshing. These features are most obvious in the N region of the cluster, where the brightness excess is the largest. The pressure varies smoothly across the spiral, consistent with a cold front.

These features are also seen in the spectral maps. The spiral can be seen tracing areas of cooler temperature, higher abundance, and lower entropy, which is consistent with a scenario where cool, metal-rich, central gas is displaced to larger radii. Temperature maps from XMM-Newton also show areas of low temperature gas tracing a spiral structure to the south, however there is no explicit mention of sloshing (Bourdin & Mazzotta 2008).

The simulations performed by Ascasibar & Markevitch (2006) and ZuHone et al. (2010) start with initial conditions for their main clusters that closely match the conditions in A2029. Thus, we can compare our observations to their simulations to put rough constraints on the merger history of A2029. The simulations that appear most similar to our observations have a mass ratio of 5 and an impact parameter of 500 kpc. From these simulations, it appears that the merger in A2029 occurred between 2 and 3 Gyr ago. To constrain the geometry of the merger, we compare our observations to A496 (Roediger et al. 2012b), which is an elliptical cluster similar to A2029. The ellipticity introduces uncertainty in the determination of the orbit orientation, however Roediger et al. (2012b) find that the large-scale structure of their residuals favors the fiducial case, where the subcluster crosses along a diagonal orbit from the SW to the N/NE. This is what we compare with A2029. Doing this, we conclude that the subcluster most likely followed an orbital path from the southeast to the northwest, passing west of the cluster center.

Sloshing features are thought to be associated with radio mini-halos, with these halos tracing the properties of the spiral (Mazzotta & Giacintucci 2008). A2029 is host to such a halo, and the morphology of the halo is similar to the morphology of the spiral (Govoni et al. 2009). The connection between the mini-halo and the spiral is not well understood, and more observations in the radio are needed to fully explore this phenomenon. It is possible that some of the energy from the sloshing is going into re-accelerating the radio-emitting relativistic particles.

The sloshing spiral is most likely distorting the central AGN, giving it a WAT morphology. This distortion will be useful for finding clusters at high redshift. Bent, double-lobed radio sources (such as the one at the center of A2029) are found in clusters \( \sim 70\% \) of the time, and thus are good tracers of clusters over a wide range of redshifts (Wing & Blanton 2011). The Mendygral et al. (2012) simulations show that these bent AGN can be found in relatively relaxed clusters, as well as in clusters where mergers have recently occurred. This will allow us to probe clusters with varying properties and to explore their evolution with redshift.
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