THE RADIO/X-RAY CONNECTION IN ABELL 2029

T. E. Clarke, E. L. Blanton, C. L. Sarazin
Department of Astronomy, Univ. of Virginia
P.O. Box 3818, Charlottesville, VA 22903
TCLARKE@VIRGINIA.EDU

Abstract

We present results of an analysis of the central regions of Abell 2029 and discuss the connections between the radio and X-ray components of the cluster. Despite the very relaxed appearance of the thermal gas in the outer cluster regions, the *Chandra* observations reveal significant structure in the cluster core. There are a number of bright X-ray filaments as well as a spiral "excess". Several of the filaments appear to be connected to the steep-spectrum cluster-center radio source PKS 1508+059. An analysis of the temperature structure in the cluster shows that the southern extension of PKS 1508+059 is surrounded by cool X-ray gas, while the northern lobe apparently lies in a region of average temperature. We also discuss the inner regions of the radio source which show two oppositely-directed, collimated jets that disrupt as the jets apparently encounter a drop in the confining thermal plasma.

1 Introduction

On global scales the thermal gas in galaxy clusters traces the structure in the cluster's gravitational potential. In the outer regions of a relaxed cluster the X-ray emission is relatively smooth and symmetric, while the inner regions often show very peaked X-ray emission which is generally interpreted as a cooling flow (Fabian, 1994). The inner regions of these cooling flow clusters are often host to large central cD galaxies with powerful radio sources. The high-resolution of the *Chandra* X-ray Observatory has revealed the details of the complex interplay between the central radio sources and the thermal intracluster medium (ICM). In these dense cluster cores the radio source can profoundly impact the structure of the thermal gas, while the confining thermal gas influences the structure and morphology of the radio source.

Radio sources associated with the dominant galaxy in cooling core clusters often reveal compact steep-spectrum morphology. X-ray observations of clusters such as Perseus (Böhringer et al., 1993; Fabian et al., 2000), Hydra A (McNamara et al., 2000) and Abell 2052 (Blanton et al., 2001) with *ROSAT* and *Chandra* show cavities (or bubbles) in the thermal gas that appear to be spatially co-incident with the radio lobes of the powerful cluster-center radio sources. The interplay between the thermal and radio plasma is complex. Contrary to predictions of supersonic expansion of radio sources (Heinz, Reynolds & Begelman, 1998), the *Chandra* observations of these cluster systems do not reveal the presence of hot gas due to shocks near the radio lobes, rather the radio sources are often surrounded by dense rims of cool gas. These observations indicate that the radio sources appear to be expanding subsonically into the ICM and displacing the thermal gas (Fabian et al., 2000; McNamara et al., 2000). This slow displacement of the X-ray gas results in the dense, bright rims of cool gas surrounding the (at least partially) evacuated cavities. The cool nature of this gas is suggested by the soft X-ray spectrum as well as optical emission lines associated with the X-ray rims seen in some cluster systems (Blanton et al., 2001; McNamara et al., 2000). In turn, the dense cluster medium is thought to confine the radio source and produce the (edge darkened) FRI structure typical of cooling flow cores. Equipartition arguments applied to the bubble systems suggest that the pressure in the radio lobes is an order of magnitude less than the surrounding thermal gas pressure (e.g., Hydra A, McNamara et al. 2000; Perseus, Fabian et al. 2000; Abell 2052, Blanton et al. 2001). Without some form of internal pressure support (such as hot, diffuse thermal gas) these X-ray depressions would collapse on sound crossing timescales of $\sim 10^7$ yr.

Here, we present an analysis of the cluster Abell 2029. Abell 2029 is located at a redshift of z = 0.0767 and contains the large central cD galaxy IC1101. Both the X-ray and optical emission are elongated along a north-east to south-west direction. The central galaxy is host to the wide-angle-tail radio source PKS 1508+059 which has two oppositely directed jets that disrupt at a distance of 10–15″ from the cluster core (Sumi, Norman & Smarr, 1988). At larger radii, the radio emission is displaced south-west of the main jet structure forming a C-shaped source typical of merging cluster systems. In standard wide angle tailed (WAT) radio sources, this C-shaped morphology is attributed to relative motions between the radio galaxy and the surrounding intergalactic medium. It has been argued that the orbital motions of a cluster-core cD radio galaxy are too small to produce the distortions (Eilek et al. 1984; O'Donoghue et al. 1993). In classical swept-back cluster-core sources, the morphology is therefore often attributed to a merger where the ICM is moving past the radio source (Burns et al. 1994).

On large scales, the thermal emission in Abell 2029 shows an exceptionally relaxed structure. Previous X-ray observations have revealed large inferred cooling-flow rates for Abell 2029 of $\dot{M} > 100\ M_{\odot}\ \mathrm{yr}^{-1}$ (e.g., Sarazin, O'Connell & McNamara, 1992; Edge, Stewart & Fabian, 1992; Peres et al., 1998; Sarazin, Wise & Markevitch, 1998, although see also White 2000; Lewis, Stocke & Buote 2002) and have suggested the presence of X-ray filaments associated with the central radio source (Sarazin, O'Connell & McNamara, 1992; Taylor, Barton & Ge, 1994). The apparently relaxed, cooling flow thermal structure is in apparent conflict with the presence of the C-shaped central radio source. We assume H_0 = 71 km s^{-1} Mpc^{-1}, Ω_Λ = 0.73, and Ω_m = 0.27. At the redshift of Abell 2029, 1″ corresponds to a linear scale of 1.44 kpc.

2 Radio and X-ray data

The galaxy cluster Abell 2029 was observed on 2000 April 12 with *Chandra* for a total of 19.8 ks. The observations were centered on the S3 chip which was operating at −120 C. The archival observations (observation ID 891) were extracted from the *Chandra* archive and reprocessed using `CIAO v2.3` and `CALDB v2.18`. The back-illuminated S1 chip was used to examine the background during the observations since the cluster emission fills the entire S3 chip. The data were free of large flares and only 128 s of data were removed.

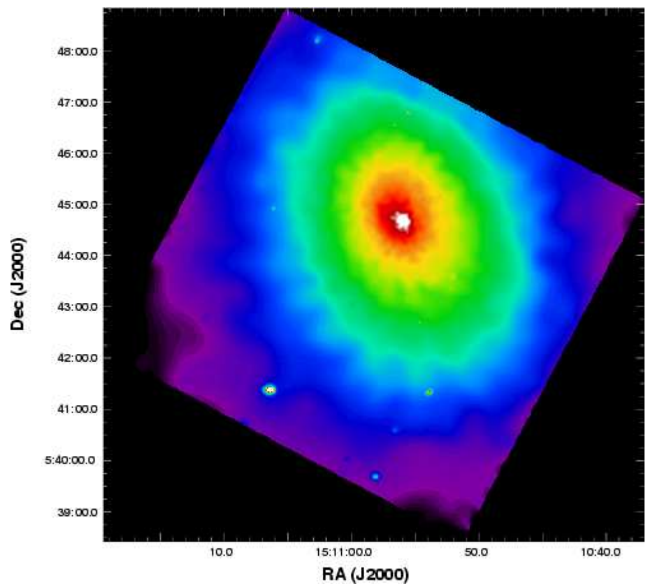

Figure 1: Adaptively smoothed 0.3–10.0 keV *Chandra* image of the entire S3 chip of Abell 2029. The entire image is roughly 780 kpc on a side. The X-ray surface brightness shows that the overall cluster emission is elongated in a north-east to south-west direction. The large scale emission is very smooth indicating a relaxed cluster morphology.

The cluster-center radio galaxy PKS 1508+059 was observed by Taylor, Barton & Ge (1994) with the Very Large Array at a variety of frequencies. They provide a detailed spatial and spectral analysis of the source in their paper. In this paper, we concentrate on the 1.4 and 8.4 GHz observations from Taylor et al.

3 Cluster properties

Optical observations of the central cD galaxy IC1101 in Abell 2029 trace the diffuse light out to radii of more than 600 kpc from the cluster core (Uson, Boughn & Kuhn, 1991), making it one of the largest known galaxies. Observations of the cluster by McNamara & O'Connell (1989) reveal that it has no optical emission lines or blue stellar continuum in the core. The lack of optical indications of star formation is unusual in a cooling core as many of these systems reveal optical nebulosity indicating the presence of star formation (e.g., McNamara & O'Connell, 1989).

Figure 1 shows the adaptively smoothed *Chandra* 0.3–10.0 keV image of the entire S3 chip. The X-ray emission appears very smooth and symmetric on large scales, consistent with the presence of a central cooling core. There are no obvious X-ray surface brightness features that indicate the presence of a major cluster

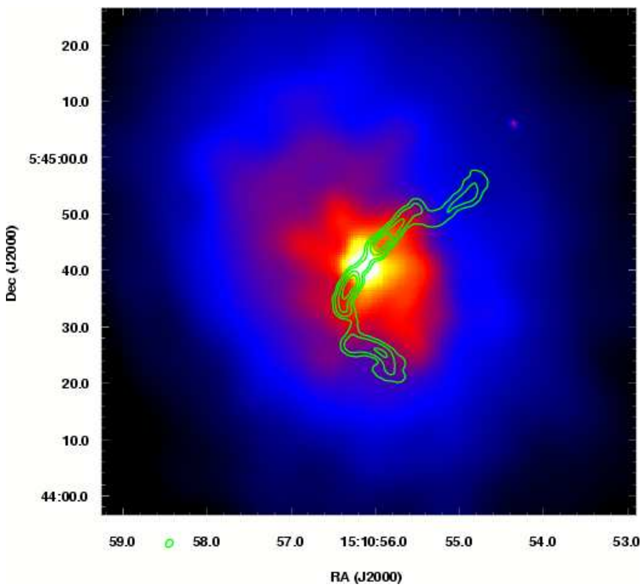

Figure 2: Adaptively smoothed 0.3–10.0 keV *Chandra* image of the central 1.5 arcminute (130 kpc) region of Abell 2029. The contours show the 1490 MHz radio emission of PKS 1508+059 from Taylor, Barton & Ge (1994). The X-ray image shows a number of broad filaments, some of which appear to be connected to the currently active radio source. The outer southern radio lobe appears to be partially surrounded by a bright X-ray rim.

merger event.

4 X-ray and radio interactions

Although the overall cluster emission in Abell 2029 appears very relaxed, there is significant structure visible in the central regions of the cluster. In Fig. 2 we show an adaptively smoothed image of the central 1.5 arcminutes (130 kpc) of Abell 2029 with the 1490 MHz radio contours of Taylor, Barton & Ge (1994) overlaid. The adaptive smoothing was done using CSMOOTH within CIAO and the X-ray image is corrected for both exposure and background. The cluster core displays a broad hourglass shape in X-rays with a number of filaments seen running to the south-west, north-west and north-east of the core. These X-ray filaments are similar to those seen in *ROSAT* HRI observations by Sarazin, O'Connell & McNamara (1992).

The central radio source displays a C-shaped morphology with two inner jets extending to distances of 10–15″, and two outer lobes extending to 20–25″. The inner jets have radio spectral indices ($S_\nu \propto \nu^\alpha$) of $\alpha = -1.4$ and $\alpha = -1.6$ between 4860 and 1490 MHz for the southern and northern jets respectively (Taylor, Barton & Ge, 1994). The steep spectral index and edge-darkened morphology are consistent with confinement of the radio source by the dense thermal intracluster medium. The inner X-ray jets appear to propagate along the pinch axis of the core and are connected to the outer lobes by faint synchrotron bridges. The spectral index of the outer lobes steepens to $\alpha \sim -3.0$. A typical extragalactic radio source has a spectral index of $\alpha = -0.7$.

The steep-spectrum southern radio lobe is partially surrounded by a bright X-ray rim which may be similar to the rims seen in sources such as Perseus (Fabian et al., 2000) and Abell 2052 (Blanton et al., 2001). An analysis of the X-ray data shows that the filament is a 9σ excess over the average counts in an annulus the width of the filament centered on the cluster core. The thermal pressure in the X-ray filament was determined by extracting a rectangular region set on the filament and fitting the data within XSPEC. The effect of the overlying ICM was modeled by using a region just exterior to the filament as a local background during the fits. The best-fit model ($\chi^2/d.o.f.$ = 38/40) gave a temperature of $kT = 4.24^{+2.91}_{-1.43}$ keV. Using the normalization of the spectrum and assuming that the emission is from a prolate cylinder, we find an electron density of n_e = 0.10 cm^{-3} and a pressure of $P_{\rm th} = 1.6\times10^{-9}$ dyne cm^{-2}. This thermal pressure is a factor of 50 larger than the minimum energy synchrotron pressure of $P_{\rm me} = 2.7\times10^{-11}$ dyne cm^{-2} determined by Taylor, Barton & Ge (1994) and converted to our cosmology. Similar (although somewhat smaller) pressure differences have been seen in several cooling core systems such as Hydra A (McNamara et al., 2000), Perseus (Fabian et al., 2000), and Abell 2052 (Blanton et al., 2001). These observations suggest the presence of an additional form of pressure support (such as a hot, thermal component) within the cavities in order to avoid the rapid collapse of the bubbles. To the north-west of the core, there appears to be an X-ray filament tracing along the edge of the inner northern radio jet. In addition to these filaments apparently connected to the radio source, there are several filaments to the north-east which have no obvious connection to the currently active radio galaxy.

Typically the rims surrounding the X-ray cavities in clusters are cooler than the surrounding gas (see, e.g., Blanton, 2004, and references therein). The cooling time of the thermal gas within the shells is often longer than the radio source lifetime, thus suggesting that the gas mainly cooled closer to the cluster core and was subsequently displaced to its current location by the radio source. For Abell 2029, the cooling time of the southern X-ray filament is $\tau_{\rm cool} = 8.4 \times 10^8$ yr. This cooling time is significantly shorter than the age of the cluster, but (as for the other systems) is much longer than the synchrotron age of the radio tail ($\tau_{\rm tail} = 1.2 \times 10^6$ yr) found by Taylor, Barton & Ge (1994). We have created a temperature map of the central region of the cluster in order to investigate the temperature structure. The map covers the central 2 kpc of Abell 2029 and has compact sources removed. Based on the lack of evidence for excess emission from the central active galactic nucleus, we have not excluded data from the cluster core. The temperature map was created within the `ISIS` software environment (Houck & DeNicola, 2000) using an adaptive binning technique. The spectra were binned to contain at least 20 counts bin^{-1}, and were fitted with a MEKAL model. The absorption was fixed at Galactic, and the abundance was set to 0.45 $Z_\odot$. The resulting temperature map is shown in Fig. 3. This map has been convolved with a Gaussian of width 1.5 pixels to smooth out the inter-pixel variations. The temperatures in the map run from roughly 3.8 keV in the core to $\sim$ 9.5 keV, with the average temperature around 6.8 keV.

The temperature map shows a triangular-shaped region of cool gas in the cluster core, surrounded by patches of cool and hot gas at larger radii. The central jets of PKS 1508+059 are completely immersed in the cool gas, and the X-ray filament tracing the southern radio tail also appears to be cool. In fact, there is additional cool gas south-east of the southern tail, suggesting that it may be surrounded by a cool shell similar to other X-ray cavities. The temperature structure shows no evidence of strong X-ray shocks associated with the radio lobes, although we cannot rule out the transfer of energy from the radio source to the thermal gas through weak shocks or pressure waves as seen in Perseus (Fabian et al., 2003). The situation appears to be significantly different for the northern radio lobe which is situated in a region of average cluster temperature. We note, however, that the relation of the gas temperature to the radio structure in the core of Abell 2029 is complicated by the X-ray excess discussed in Sect. 5.

On smaller scales, the inner radio jets appear to be

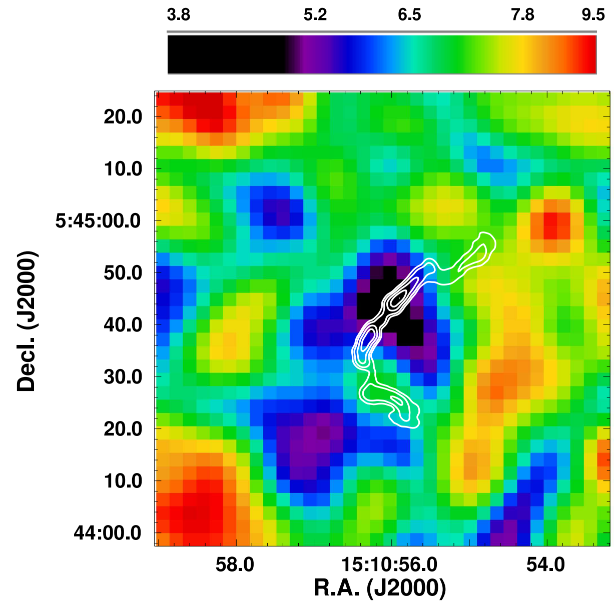

Figure 3: Temperature map of the central 2 kpc of Abell 2029 with the color scale shown on top in units of keV. The cluster gas is coolest in the center (around 3.8 keV) and shows cool gas associated with the filament near the southern radio tail. The northern radio tail appears to be embedded in a region of average cluster temperature. The temperature structure in the core of the cluster is complex, likely due to the superposition of the spiral excess feature and the X-ray filaments.

well collimated to distances of $\sim 2''$ (3 kpc) from the core. Figure 4 shows the 8.5 GHz radio contours from Taylor, Barton & Ge (1994) overlaid on the adaptively smoothed *Chandra* image of the central 30 kpc region of Abell 2029. The inner jets appear to propagate along the pinch axis of the X-ray core. Beyond a distance of 3 kpc both radio jets flare outward and broaden by a factor of more than three in width. The location of the de-collimation is co-incident with a sharp drop in the X-ray surface brightness as seen in Fig. 4. The sharp X-ray surface brightness drop suggests that the de-collimation of the radio jets is likely due to a decrease in the confining pressure of the external thermal ICM. A similar flaring is seen in the jets of 3C31 where Laing & Bridle (2002) find that the jets are overpressured by a factor of $\sim$ 8 with respect to the confining medium at the flaring point.

An alternative method to de-collimate the jets would be through the interaction of the radio jet with dense gas clumps in the ICM. Unfortunately there is insufficient X-ray data in the jet and de-collimation regions to allow us to study the detailed spectral properties of the thermal gas. Beyond the flaring point, the 8.5 GHz radio jets continue to propagate to a distance of $\sim 10''$ ($\sim$ 15 kpc). The northern jet appears to follow a linear trajectory, while the tip of the southern jet shows a curvature toward the south. The radio morphology of the southern jet appears to trace the cool X-ray filament which extends south of the cluster core. The end of the southern jet appears to bend toward the south along the edge of the thermal filament.

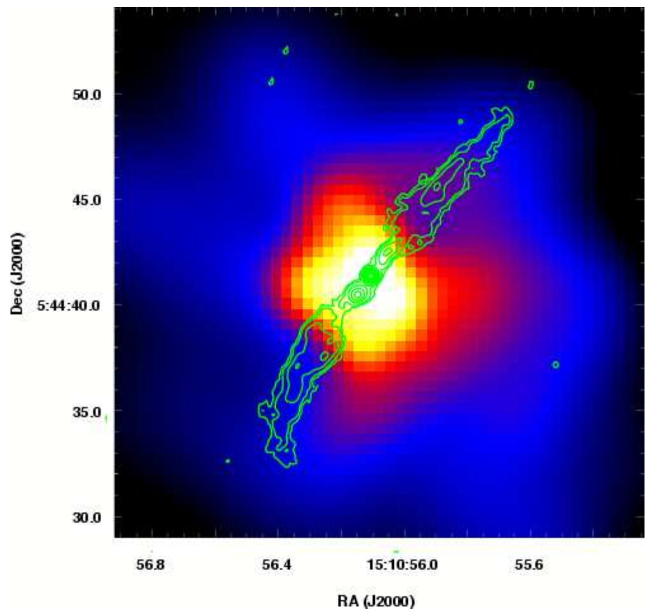

Figure 4: Adaptively smoothed 0.3–10.0 keV *Chandra* image of the central 30 kpc region of Abell 2029. The contours show the 8515 MHz radio contours of PKS 1508+059 from Taylor, Barton & Ge (1994). The X-ray image shows a broad core with an hourglass shape. The inner radio jets appear to propagate along the pinch axis of the broad core.

5 Spiral excess

The large scale diffuse X-ray emission in Abell 2029 is not symmetrically distributed about the cluster core. On large scales the X-ray emission is extended in a north-east to south-west direction, similar to the optical cD emission observed by Uson et al. (1991). In addition, there is a strong decrease in surface brightness $\sim$ 20 kpc to the west of the cluster core and a much more gradual decrease in the other directions. More generally, there appears to be excess emission to the north-east and south-east compared to the south-west and north-west, respectively. This lack of mirror-symmetry has been previously reported from the *ROSAT* HRI data (Sarazin, O'Connell & McNamara, 1992).

To investigate the details of the structure in this cluster we have fit the background and exposure corrected X-ray emission with a smooth elliptical model using the `IRAF` task ELLIPSE. We have centered the model on the cluster core and allowed the intensity, ellipticity and position angle of the model to vary within each aperture. The data were fit from a radius of 3 kpc ($\sim 2''$) to a semi-major axis radius of 310 kpc ($3.6'$). The best-fit model was then subtracted from the input X-ray image to produce the residual image shown in Fig. 5 (where we have also overlaid the 1.4 GHz radio contours of Taylor, Barton & Ge (1994)). The residuals display a striking bipolar spiral pattern which can be seen to radii of at least 130 kpc. The positive and negative residuals are each at roughly the 15% level. We have examined the robustness of the residuals by investigating a number of models with various combinations of freeing and fixing the centroid, ellipticity and position angle. We find that all models reproduce essentially the same structure with only slight differences in the very core. We have also masked out the region of positive residuals and fit the elliptical model to the remainder of the emission to obtain a model for subtraction. This technique again produced similar structure but has the advantage of removing the negative residuals. In addition to the spiral pattern, the residual image also clearly shows the linear absorption feature 1.5 arcminutes south of the cluster core which is due to photoelectric absorption by a foreground edge-on spiral galaxy (Clarke et al., 2004).

We have extracted an X-ray spectrum from the region of bright excess and a comparison region rotated 180° about the cluster center. Both regions were fit with single temperature MEKAL models within `XSPEC` with the absorption fixed to Galactic and the temperature and abundances left as free parameters. The fits show that the region containing the excess is slightly cooler ($\sim$ 1 keV) on average than the comparison region at the 90% confidence level. The 1.4 GHz radio contours overlaid on Fig. 5 show that the excess extends well beyond the central radio source and thus is not likely a result of interactions of the thermal and radio plasmas. One possible interpretation of the excess is that it is a remnant from the infall of a cold cloud of gas which has fallen into the cluster center with initial non-zero angular momentum. The gas may have been associated with a galaxy or group of galaxies which merged with Abell 2029, or it might have been purely gaseous,

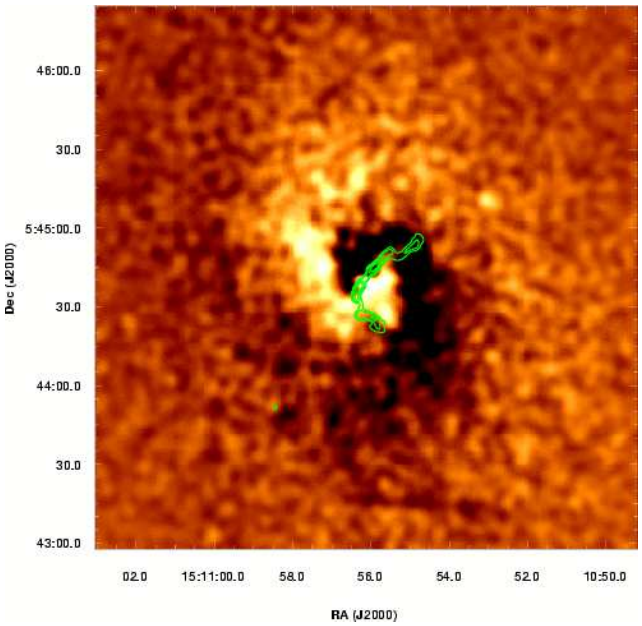

Figure 5: Residual image of the central 275 kpc of Abell 2029. The image was made by subtracting a smooth elliptical model from the Gaussian (σ = 2″) smoothed *Chandra* data. Contours show the 1.4 GHz radio emission of PKS 1508+059 from Taylor, Barton & Ge (1994). The large spiral X-ray excess may be the result of stripping of gas from an infalling cold cloud that had an initial non-zero angular momentum orbit. The linear feature seen 1.5 arcminutes south of the cluster core is an absorption region associated with the disk of a foreground edge-on spiral galaxy.

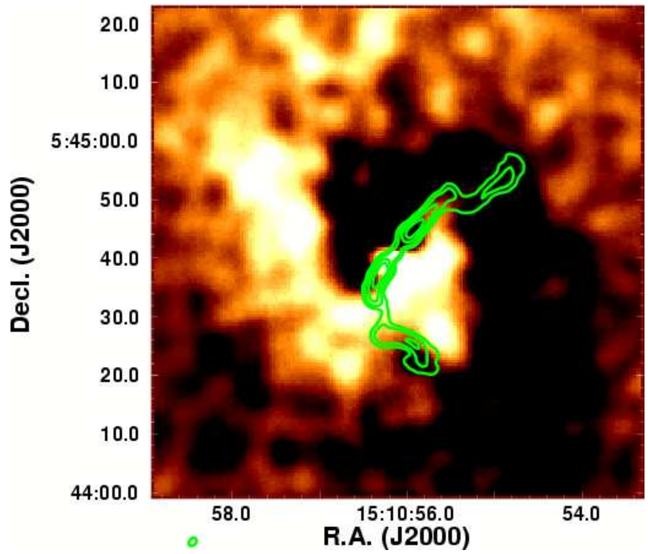

Figure 6: Residual image of the central 2 kpc of Abell 2029 with VLA 1490 MHz radio data of Taylor, Barton & Ge (1994) overlaid. The central portion of the X-ray excess can be seen to run between the inner southern jet and the outer radio lobe.

or gas occupying a dark matter potential well. We have estimated the mass of gas required to produce the observed excess and find $M_{\rm spiral} \sim 6\times10^{12}\ M_{\odot}$. It is likely that this is a lower limit to the mass required as the mass in the spiral is increasing rapidly with radius over the range observed with *Chandra* and *XMM-Newton* observations suggest that the excess feature is more extended than we see here.

Alternatively, the spiral feature might be the result of sloshing motions in the core of the cluster, perhaps induced by a past cluster merger (as suggested by Maxim Markevitch during this talk). Sloshing features, have been observed in a number of cooling flow clusters (e.g., Markevitch et al., 2001), but not in the form of extended spirals. It might be possible to generate a spiral sloshing feature in an offset merger with significant angular momentum. Short spiral features are seen in some merger simulations (see, e.g., Motl, 2005, these proceedings), but they generally are stronger shocks and occur during very strong mergers. Whether weaker spiral sloshing features can persist long after a merger in an apparently relaxed cluster like Abell 2029 is uncertain.

In Fig. 6 we show the central region of the X-ray excess with the 1490 MHz radio contours of PKS 1508+059 overlaid. The excess appears to run (in projection) directly between the inner southern jet of the radio source and the steep-spectrum outer radio lobe. On the other hand, the northern radio extension appears to be situated at radii interior to the excess and is thus not expected to be affected by the spiral system. As discussed above, in the standard model of WAT radio sources, the C-shaped morphology is thought to be the result of relative motion between the radio galaxy and the surrounding intergalactic medium. For cluster-center sources, the structure is often attributed to a merger event where the ICM is flowing past the radio source (Burns et al., 1994). In the case of Abell 2029, it is possible that the interaction of the infalling material with the radio source has led to the unusual C-shaped radio morphology in an apparently relaxed cluster. The bend in the tip of the southern jet at the location where the spiral is seen in projection is strongly suggestive of an interaction. There are still many unanswered questions regarding the complex radio and X-ray interactions within the core of this system. We will continue to investigate this intriguing system with our new 80 ks

Chandra Cycle 5 data.

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