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Radio and X-Ray Interactions in the Core of Abell 2029

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Observations with *Chandra* have shown that radio sources and the dense ICM in the cores of clusters of galaxies can have a profound effect on one another. In many cases, cavities or "bubbles" are created in the X-ray gas, and the central radio sources often reveal distorted morphologies. We present *Chandra* observations of the galaxy cluster Abell 2029, which contains a dense X-ray core and a central steep-spectrum radio source. The central regions of the cluster reveal complex X-ray structures. We discuss the connection between the X-ray substructure and the central radio source (PKS 1508+059).

1. Introduction

In a relaxed galaxy cluster, X-ray observations reveal that the outer regions of the cluster show a relatively smooth and symmetric surface brightness distribution, 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).

X-ray observations of clusters such as Perseus (Böhringer et al. 1993; Fabian et al. 2000), Hydra A (McNamara 2000) and Abell 2052 (Blanton et al. 2001) with ROSAT and *Chandra* show depressions (or bubbles) in the thermal gas that appear to be spatially co-incident with the radio lobes. 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 X-ray shocks near the radio lobes, rather the radio sources appear to be expanding subsonically into the ICM and displacing the thermal gas (Fabian et al. 2000; McNamara 2000). This slow displacement of the X-ray gas results in bright rims of cool gas observed along the edges of the radio lobes. 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 2000). In turn, the dense cluster medium is thought to confine the radio source and produce the (edge darkened) FR I 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 IC 1101. 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. Previous X-ray observations have revealed large inferred cooling-flow rates for Abell 2029 of $\dot{M} > 100\ M_\odot$ 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). 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. Data Reductions

Abell 2029 was observed on 2000 April 12 with *Chandra* for a total of 19.8 ksec. 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.

3. X-ray and Radio Interactions

In Figure 1 we show an adaptively smoothed image of the central 1.′5 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 central radio source displays a *C*-shaped morphology with two inner jets extending to distances of 10–15$''$, and two outer steep-spectrum

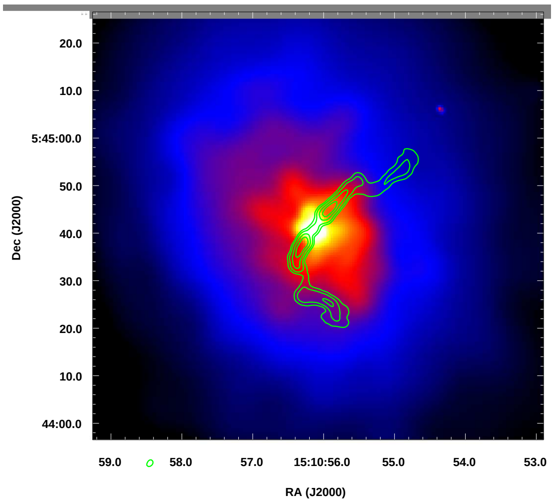

FIG. 1.— Adaptively smoothed 0.3–10.0 keV *Chandra* image of the central 1′.5 (130 kpc) region of Abell 2029. The contours show the 1490 MHz radio contours of PKS 1508+059 from Taylor, Barton, & Ge (1994). The X-ray image shows a number of broad filaments, some of which appear to be connected to the currently active radio source. The outer southern radio lobe appears to be partially surrounded by a bright X-ray rim.

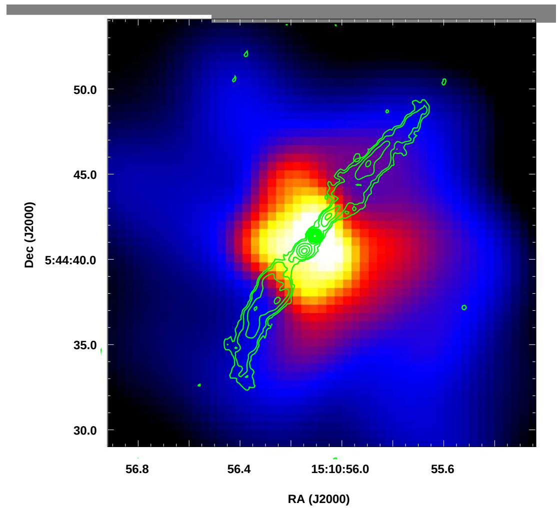

FIG. 2.— Adaptively smoothed 0.3–10.0 keV *Chandra* image of the central 30 kpc region of Abell 2029. The contours show the 8515 MHz radio contours of PKS 1508+059 from Taylor, Barton, & Ge (1994). The X-ray image shows a broad core with an hourglass shape. The inner radio jets appear to propagate along the pinch axis of the broad core.

lobes extending to 20–25″. The inner jets appear to be connected to the outer lobes by a faint synchrotron bridge. The smoothed X-ray image clearly shows significant structure in the central regions of Abell 2029. The cluster core displays an hourglass shape with the inner radio jets propagating along the pinch axis (Figure 2). The inner jets appear to be well collimated to distances of $\sim 2''$ (3 kpc) from the core, at which point they de-collimate at the location of the drop in the X-ray surface brightness. Beyond the broad core, there are a number of X-ray filaments visible extending radially outward. The steep-spectrum southern radio lobe appears to be 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). To the north-west of the cluster 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.

4. **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). 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. 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

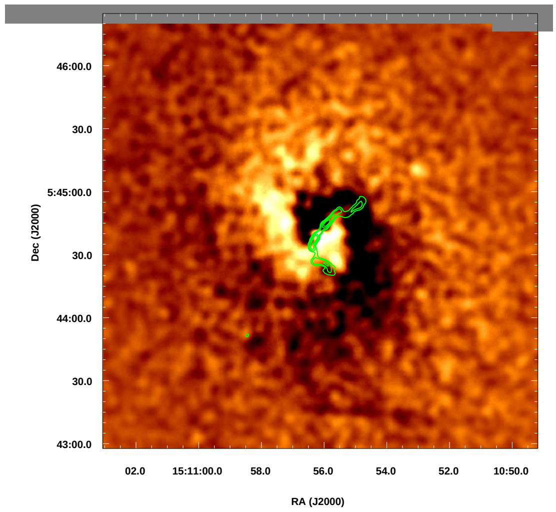

FIG. 3.— Residual image of the central 275 kpc of Abell 2029. The image was made by subtracting a smooth elliptical model from the Gaussian ($\sigma = 2''$) smoothed *Chandra* data. Contours show the 1.4 GHz radio emission of PKS 1508+059 from Taylor, Barton, & Ge (1994). The large spiral X-ray excess 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 south of the cluster core is an absorption region associated with the disk of a foreground edge-on spiral galaxy.

image to produce the residual image shown in Figure 3 with the 1.4 GHz radio contours of Taylor, Barton, & Ge (1994) overlaid. The residuals display a striking dipolar spiral pattern which can be seen to radii of at least 130 kpc. The residual image also clearly shows the linear absorption feature 1′.5 south of the cluster core (see discussion in § 4). 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

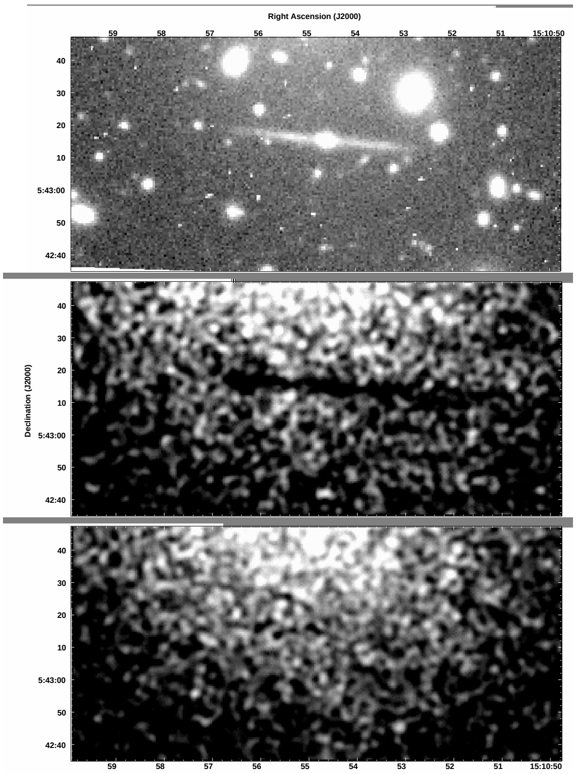

FIG. 4.— The top panel shows the KPNO 0.9m I-band image of the spiral galaxy UZC J151054.6+054313. The middle panel shows the Gaussian smoothed (σ=1″) 0.3–1.0 keV *Chandra* soft X-ray image, and the bottom panel contains the *Chandra* 1.0–7.0 keV hard X-ray image. comparison of the soft and hard X-ray images clearly reveals the photoelectric absorption feature due to the foreground spiral galaxy. The gradient in surface brightness seen north to south is due to the ICM near the core of Abell 2029.

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 cooler on average than the comparison region at the 90% confidence level. 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 1.4 GHz radio contours overlaid on Figure 3 show that the excess appears to run (in projection) directly between the inner southern jet of PKS 1508+059 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 infalling system. In the standard model of wide-angle-tailed 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.

5. Foreground Spiral

The *Chandra* observations of Abell 2029 show a linear, nearly east-west X-ray depression located roughly 1.′5 south of the cluster core. Comparison of the hard and soft X-ray images of the cluster show that the X-ray depression is consistent with photoelectric absorption (Clarke et al. 2004). Optical images indicate that the absorption is due to the foreground ($z = 0.0221$) spiral galaxy UZC J151054.6+054313. Figure 4 shows the I-band image from the KPNO 0.9m telescope and the *Chandra* 0.3–1.0 and 1.0–7.0 keV X-ray images.

Optical data suggest that the foreground galaxy is an Scd galaxy seen nearly edge-on, at an inclination of $87° \pm 10°$. H I observations from the Green Bank Telescope give a total mass of $M_{HI} = 3.1 \times 10^9\ M_\odot$, while the X-ray absorption data gives a total hydrogen mass of $M_H = 6.2 \times 10^8\ M_\odot$.

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