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DISCOVERY OF GHOST CAVITIES IN THE X-RAY ATMOSPHERE OF ABELL 2597

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ABSTRACT

A *Chandra* image of the central 100 kpc of the Abell 2597 cluster of galaxies shows bright irregular X-ray emission within the central dominant cluster galaxy (CDG) and two low surface brightness cavities located 30 kpc from the nucleus of the CDG. Unlike the cavities commonly seen in other clusters, the "ghost" cavities in Abell 2597 are not coincident with the bright central radio source. Instead, they appear to be associated with faint extended radio emission seen in a deep Very Large Array radio map. We interpret the ghost cavities as buoyantly rising relics of a radio outburst that occurred between 50 and 100 Myr ago. The demography of cavities in the few clusters studied thus far shows that galactic radio sources experience recurrent outbursts on an ~100 Myr timescale. Over the lifetime of a cluster, ghost cavities emerging from CDGs deposit $\gtrsim 10^{59}$–10^{61} ergs of energy into the intracluster medium. If a significant fraction of this energy is deposited as magnetic field, it would account for the high field strengths in the cooling flow regions of clusters. The similarity between the central cooling time of the keV gas and the radio cycling timescale suggests that feedback between cooling gas and the radio source may be retarding or quenching the cooling flow.

Subject headings: cooling flows — galaxies: clusters: general — intergalactic medium —
radio continuum: galaxies — X-rays: galaxies: clusters

1. INTRODUCTION

Early *Chandra* images of galaxy clusters have shown that the X-ray–emitting gas in their centers is bright and irregularly structured and that much of this structure is associated with powerful radio sources. The radio sources in the Hydra A (McNamara et al. 2000b), Perseus (Fabian et al. 2000), and Abell 2052 (Blanton et al. 2001) clusters appear to have pushed aside the keV gas, leaving low surface brightness cavities in the gas. The cavities in Hydra A, Perseus, and Abell 2052 are filled with bright radio emission and are confined by the pressure of the surrounding keV gas. The cavities may be supported against collapse by pressure from relativistic particles, magnetic fields, and/or hot, thin thermal gas. Since the cavities have a lower gas density than their surroundings, they should behave like bubbles in water and rise buoyantly in the intracluster medium (ICM; McNamara et al. 2000b; Churazov et al. 2001).

Using simulations of supersonic jets expanding into the ICM, Clarke, Harris, & Carilli (1997) and Heinz, Reynolds, & Begelman (1998) argued that the cavities seen in *ROSAT* images of the ICM surrounding the Perseus and Cygnus A radio sources (Heinz, Reynolds, & Begelman 1992; Carilli, Perley, & Harris 1994) were caused by strong shocks. In this instance, the X-ray emission from the rims surrounding the cavities should be spectrally hard, and gas in the rim should have higher entropy than the surrounding gas. The initial *Chandra* results for the Hydra A (McNamara et al. 2000b; Nulsen et al. 2001), Perseus (Fabian et al. 2000), and Abell 2052 (Blanton et al. 2001) clusters were surprising, as the emission from the rims of the cavities was among the softest in the clusters. This implies that the radio lobes expanded gently into the ICM at roughly the sound speed in the keV gas (Reynolds, Heinz, & Begelman 2001; David et al. 2000; Nulsen et al. 2001). The rapidly growing number of cavities found in giant elliptical galaxies (Finoguenov & Jones 2000), groups (e.g., Vrtilek et al. 2000), and central dominant cluster galaxies (CDGs; e.g., Schindler et al. 2001) indicates that they are persistent features of these systems.

An intriguing and potentially significant *Chandra* discovery is the existence of cavities in the keV gas that do not have bright radio counterparts. If such "ghost" cavities, as are seen in Perseus (Fabian et al. 2000) and in Abell 2597 (discussed here and in McNamara et al. 2000a), are generated by radio sources, their properties would have significant consequences for our understanding of the life cycles of radio galaxies and the origin and dispersal of magnetic fields in clusters and galaxies. Here we discuss the remarkable properties of the X-ray core of Abell 2597 and its ghost cavities. Throughout this Letter, we assume $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, a luminosity distance of 374 Mpc, and $1'' = 1.67$ kpc.

2. OBSERVATIONS AND DATA REDUCTION

Abell 2597 is an $L_X = 6.45 \times 10^{44}$ ergs s^{-1} (2–10 keV; David et al. 1993), richness class 0 cluster that lies at redshift $z = 0.083$. The cluster possesses a bright cusp of X-ray emission associated with a cooling flow and the powerful radio source PKS 2322−122, both centered on the CDG (Sarazin et al. 1995).

A 40 ks *Chandra* exposure was taken of Abell 2597 on 2000 July 28. The nucleus of the CDG was centered on node 0 of the ACIS-S3 back-illuminated device. The pointing was chosen to maximize the spatial resolution and soft energy response available with *Chandra* while avoiding placing the interesting central region on a node boundary. The observations were made in faint, full-frame timed exposure mode, with the focal plane

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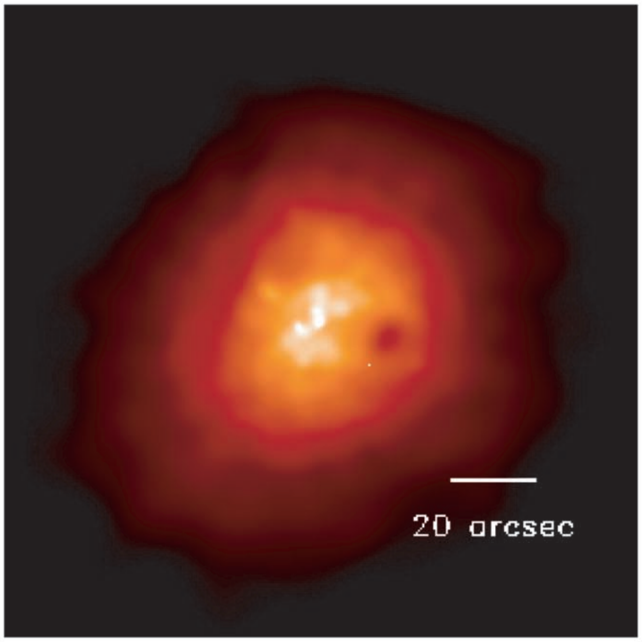

FIG. 1.—Broadband-smoothed X-ray image of Abell 2597. The surface brightness is irregular in the central 40″. The surface brightness depressions associated with the cavities are seen 18″ to the southwest and northeast of center. North is at the top; east is to the left.

FIG. 2.—Expanded view of the central region of Abell 2597 after subtracting a smooth background cluster model. The 8.44 GHz radio contours are superposed. The cavities are seen as indentations in the bright emission. North is at the top; east is to the left.

at a temperature of −120°C. Grades 1, 5, and 7 were rejected in our analysis, as were data below 0.3 keV and above 8.0 keV. Unfortunately, the observations were compromised by strong flares. As a consequence, only 18.54 ks of useful data were gathered.

3. COMPARISON BETWEEN THE CENTRAL X-RAY AND RADIO STRUCTURES

An adaptively smoothed X-ray image of the central 150″ × 150″ centered on the CDG is shown in Figure 1. The passband of this image is from 0.3 to 8.0 keV. The image immediately reveals the gross structure in the inner 1′ or so of the cluster, first seen in an earlier *ROSAT* High Resolution Imager observation (Sarazin et al. 1995). However, the fine structure and particularly the surface brightness depressions located 18″ to the southwest and 16″ to the northeast of the center were not seen in the *ROSAT* image.

The central structure was isolated by modeling and subtracting the smooth background cluster emission, leaving the excess emission shown in Figure 2. This difference image was then adaptively smoothed, which revealed the structure shown above the 4 σ significance level. In the bright regions, surface brightness variations of 50%–60% are present. The large surface brightness depressions to the northeast and southwest are 2–3 times fainter than the surrounding regions, the depression to the southwest being deeper. In order to examine the relationship between the central radio source and the structure in the gas, we have superposed radio contours of Abell 2597 in Figure 2. The radio image was obtained with the Very Large Array (VLA) A configuration, tuned to a frequency of 8.44 GHz (Sarazin et al. 1995). The radio source is relatively small and has a steep spectrum with a spectral index of about equal to −1.5 (O'Dea, Baum, & Gallimore 1994; Sarazin et al. 1995). Its full extent from north to south is only 5″, or roughly 8 kpc. Although a great deal of structure is seen surrounding the radio source, there is no evidence for cavities there in spite of its powerful nature. However, the central radio source is small compared to the bright X-ray structure in the inner 40 kpc or so. Therefore, any cavities that may exist would be difficult to detect owing to emission from intervening material along the line of sight.

Unlike the cavities in Hydra A, cavities in Abell 2597 are located at larger radii and are more than twice the size of the central radio source. After subtracting the background cluster, the cavities appear to be more extensive than the impression given in Figure 1. The cavity to the northeast is roughly circular, with a ≃9″ diameter, corresponding to a linear diameter of 15 kpc. The cavity to the southwest is elliptically shaped with major and minor axes ≃14″ and ≃9″, or 23 and 15 kpc linear diameter, respectively. The cavities are surrounded by shells of X-ray gas on most sides, but perhaps not at the outermost radii. We divided the data into soft- and hard-band images with 0.5–1.5 and 1.5–3.5 keV passbands, respectively, and we arrived at the following conclusions. To within the accuracy of the data, (1) the emission immediately adjacent to each cavity is generally no harder or softer than its surroundings, and (2) deep surface brightness depressions are present in both bands. Therefore, there is no compelling evidence for heating by the agent that inflated the cavities, nor are the depressions likely to be caused by absorption.

In order to determine whether faint radio emission is associated with the cavities, radio observations of Abell 2597 were made with the VLA at 1.4 GHz on 2001 June 21. The total observing time was 12 hr, and the array configuration was mixed between the 3 km and 10 km configurations, leading to a synthesized beam of FWHM = 11″ × 6″ with the major axis position angle of 90°. Standard amplitude and phase calibration were applied, as well as self-calibration using sources in the field. The dominant source in the field is the nucleus of Abell 2597 itself (Fig. 2), which has a peak surface brightness in our 1.4 GHz image of 1.49 ± 0.03 Jy beam^{-1}. This bright source limits the sensitivity of the final image to about 0.1 mJy beam^{-1}

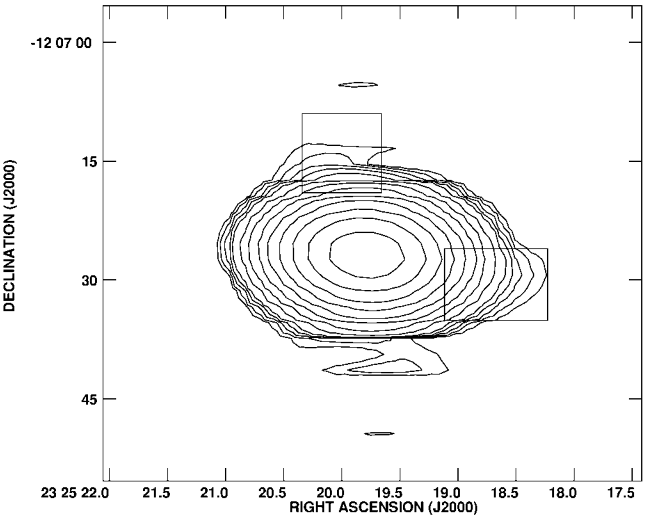

FIG. 3.—VLA 1.4 GHz image of Abell 2597 at 11″ × 6″ resolution (*oval contours*), with the major axis position angle of 90°. The first five contour levels are a geometric progression in the square root of 2, with the first level being 0.9 mJy beam^{-1}. The higher contours are a geometric progression by factors of 2. Boxes correspond roughly to the positions and sizes of the X-ray cavities. The faint contours extending south of center are data artifacts.

rms, implying a dynamic range of 15,000. The radio emission from Abell 2597 is marginally resolved with these observations, with a total flux density of 1.82 Jy.

In the context of studying the X-ray cavities, the most interesting results from the radio observations are the extensions of the radio source in the vicinity of the cavities, as can be seen in Figure 3. These extensions are robust in the imaging process and are highly significant with respect to the noise on the image. Unfortunately, the resolution of the image is inadequate to make any firm conclusions concerning the morphology of the extended emission in the vicinity of the cavities, only that such emission exists. This detection of radio emission and a future confirmation with higher resolution are keys to understanding the nature of ghost cavities (§ 5).

4. THE PHYSICAL STATE OF keV GAS

The radial distribution of surface brightness, temperature, electron density, and pressure in the central region of Abell 2597 is shown in Figure 4. The profiles were extracted from annular apertures centered on the weak nuclear point source coincident with the radio core (R.A. = $23^{\mathrm{h}}25^{\mathrm{m}}19\overset{\mathrm{s}}{.}7$, decl. = 12°07′27″ [J2000.0]). The aperture sizes were chosen to include roughly 1000 and 5000 counts for surface brightness and temperature profiles shown in Figures 4*a* and 4*c*, respectively. The density profile, Figure 4*b*, was constructed by deprojecting the surface brightness profile assuming an emission measure appropriate for a 3 keV gas. The temperature in each aperture was determined by fitting an absorbed MEKAL single-temperature model in XSPEC with abundances fixed at 0.4 solar and a Galactic foreground column of $N_{\mathrm{H}} = 2.48 \times 10^{20}\ \mathrm{cm}^{-2}$. Only data from the ACIS-S3 device were considered.

The temperature drops from 3.4 keV at 100 kpc to 1.3 keV in the inner several kiloparsecs. Over this same region, the gas density and pressure rise dramatically, reaching values of 0.07–0.08 cm^{-3} and 2.5×10^{-10} ergs cm^{-3}, respectively, in the inner few kiloparsecs. The radiative cooling time of the keV gas in the central 10 kpc region surrounding the radio source is only $\approx 3 \times 10^{8}$ yr. Similar properties are found in other cooling flow clusters, such as Hydra A (McNamara et al. 2000a, 2000b; David et al. 2000), Abell 2052 (Blanton et al. 2001), and Perseus (Fabian et al. 2000).

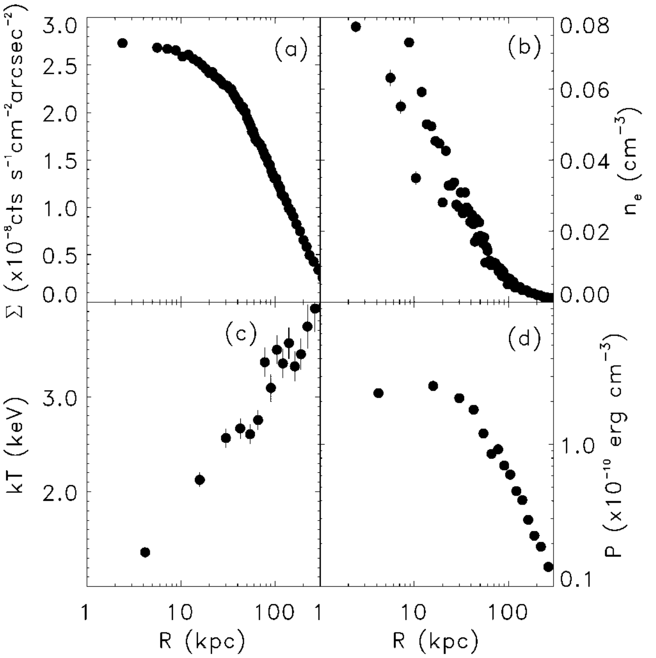

FIG. 4.—Radial variation of (*a*) surface brightness, (*b*) electron density, (*c*) temperature, and (*d*) pressure.

5. THE ORIGIN AND ENERGY CONTENT OF THE GHOST CAVITIES

Without internal pressure support, the cavities would collapse on the sound crossing timescale of $\sim 10^{7}$ yr. Yet the existence of ghost cavities in Abell 2597 and in NGC 1275 (Fabian et al. 2000) beyond their radio lobes shows that they almost certainly persist much longer than 10^{7} yr and therefore must have pressure support. The gas density within the ghost cavities is much less than the ambient density. Therefore, they must be buoyant and have risen outward from the nucleus to their current projected radii of $\simeq 30$ kpc. The time required for the cavities to rise to this radius is roughly $10^{7.7}$–10^{8} yr (McNamara et al. 2000b; Churazov et al. 2001). This is much larger than the minimum age of the central radio source of $\sim 5 \times 10^{6}$ yr (Sarazin et al. 1995), so the ghost cavities are unlikely to be related directly to the current nuclear radio episode.

Based on the properties of radio-bright cavities, it is reasonable to suppose that the ghost cavities were produced in a radio episode that predated the current one shown in Figure 2. Their radio emission has faded presumably because they are no longer being supplied with relativistic particles from the nucleus. This hypothesis is supported by our detection of extended radio emission toward the cavities and their locations along nearly the same position angle as the central jets (Sarazin et al. 1995). A rough estimate of the minimum energy pressure in the extended, 1.4 GHz emission is considerably less than the ambient pressure, as is found in other clusters. This would suggest a departure from the minimum energy condition or a dominant pressure contribution from low-energy electrons or protons.

Assuming the cavities formed through the action of a radio source, the lower limit to the energy expended during their formation is given by the $P\,dV$ work done on the surrounding gas. The gas pressure at the radius of the cavities is $\simeq 2.1 \times 10^{-10}$ ergs cm^{-3}. Assuming the cavities are projected spheroids with volumes of $\approx 5 \times 10^{67}$ and $\approx 1 \times 10^{68}$ cm^3 for the northeast and southwest cavities, respectively, the minimum energy corresponds to $\sim 3.4 \times 10^{58}$ ergs. The figure could be 2–3 times larger if one included the energy of thermal and relativistic gas in the cavities. This energy is more than an order of magnitude larger than the total mechanical energy of the central radio source (Sarazin et al. 1995). Therefore, if the ghost cavities originated in an earlier radio event, it would have been as powerful in the past as Hydra A.

6. DISCUSSION

The existence of ghosts cavities and their likely association with radio sources directly implies that powerful radio sources occur in repeated outbursts. This is consistent with the fact that more than 70% of CDGs in clusters with bright X-ray cusps—cooling flows—harbor powerful radio sources, while less than 20% of CDGs in noncooling flow clusters are radio bright (Burns 1990). It would seem then that radio sources in cooling flow CDGs have the shortest duty cycles among the elliptical galaxies. The time required for cavities to rise to their observed locations implies radio cycling every 50–100 Myr. The alternative interpretation of the high incidence of radio emission that radio sources persist on gigayear timescales appears to be inconsistent with the existence of ghost cavities.

The cooling time of the central keV gas, $\approx 3 \times 10^{8}$ yr, is interestingly close to the radio cycling timescale. This implies that feedback between radio heating and radiative cooling may be operating there (Tucker & David 1997; Soker et al. 2001). The energy deposited by cavities into the ICM in the form of magnetic fields, cosmic rays, and heat over the life of the cluster is $\gtrsim 10^{60}$–10^{61} ergs, assuming the CDG produces between 10 and 100 bubbles over its lifetime. This is roughly equivalent to the cooling luminosity of an approximately 50 $M_\odot$ yr^{-1} cooling flow in the center of the cluster. While this energy could reduce and possibly quench a small cooling flow, there is scant evidence for direct heating by radio sources (McNamara et al. 2000a, 2000b; Fabian et al. 2000; David et al. 2001). However, bulk lifting of cooling material out of cluster cores where it will expand, mix with ambient gas, and cool less efficiently can assist in reducing the deposition of cooled gas without the direct introduction of heat. (David et al. 2001; Nulsen et al. 2001).

Finally, clusters are magnetized (Clarke, Kronberg, & Böhringer 2001; Kronberg et al. 2001), and cavities emerging from the CDGs and normal elliptical galaxies in clusters may be vessels that transport magnetic fields from galaxy nuclei to the ICM. If a significant fraction of the 10^{60}–10^{61} ergs of energy emerging from CDGs alone were deposited as magnetic field in the inner 100 kpc of clusters, the implied field strengths of ~ 5–50 μG would be consistent with the field strengths observed in the cores of cooling flow clusters (Ge & Owen 1993).

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