THE EFFECT OF A CHANDRA-MEASURED MERGER-RELATED GAS COMPONENT ON THE LOBES OF A DEAD RADIO GALAXY

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ABSTRACT

We use Chandra data to infer that an X-ray–bright component of gas is in the process of separating the radio lobes of 3C 442A. This is the first radio galaxy with convincing evidence that central gas, overpressured with respect to the lobe plasma and not simply a static atmosphere, is having a major dynamical effect on the radio structure. We speculate that the expansion of the gas also reexcites electrons in the lobes of 3C 442A through compression and adiabatic heating. Two features of 3C 442A contribute to its dynamical state. First, the radio source is no longer being powered by a detected active jet, so that the dynamical state of the radio plasma is at the mercy of the ambient medium. Second, the two early-type galaxies, NGC 7236 and NGC 7237, one of which was the original host of 3C 442A, are undergoing a merger and have already experienced a close encounter, suggesting that the X-ray–bright gas is mostly the heated combined galaxy atmospheres. The lobes have been swept apart for \( \sim 10^8 \) yr by the pressure-driven expansion of the X-ray–bright inner gas.

Subject headings: galaxies: active — galaxies: individual (NGC 7237, 3C 442A) — galaxies: interactions — radio continuum: galaxies — X-rays: galaxies

1. INTRODUCTION

Radio galaxies have a profound influence on the intergalactic, intragroup, or intracluster X-ray–emitting gas in which they are in contact, in particular through moving gas via the creation of cavities and shocks (see the review of Jones et al. 2007). In turn, the dynamics of the radio plasma are affected by the inertia of the gas that it encounters, and it is slowed and redirected as a result. In this Letter, we report the first case where, instead of radio plasma moving X-ray–emitting gas, the X-ray–emitting material is exerting a dominant influence on old radio plasma, pushing apart the lobes of 3C 442A.

Birkinshaw et al. (1981) first reported on the absence of jet emission in the amorphous radio lobes of 3C 442A, and this is confirmed by the more extensive study of Comins & Owen (1991); 3C 442A can therefore be characterized as a dead radio galaxy, in the sense that it contains no radio jet at the level seen in actively jet-driven radio galaxies of similar power.

A pair of similar mass early-type galaxies, NGC 7236 and NGC 7237, lie between the radio lobes of 3C 442A. Borne & Hoessel (1988) provide strong evidence that these two galaxies, which are a part of group containing also a fainter member, are undergoing a merger, and an interaction model for the binary system is fitted to the data by Borne (1988).

Our ROSAT High Resolution Imager observation of 3C 442A showed extended emission elongated in the north-south direction and lying between the two lobes (Hardcastle & Worrall 1999), but the relatively low sensitivity of the observation and the lack of X-ray spectral information prevented the physical relationship between the gas and radio plasma from being addressed. This has been corrected through a deep Chandra observation of the source. In this Letter, we show that X-ray gas is pressing on and separating the lobes of the radio galaxy. A more complete discussion of the X-ray gas, including that surrounding the lobes and the filamentary small-scale structure, is presented elsewhere (Hardcastle et al. 2007).

The average recession velocity of the galaxy pair NGC 7237 and NGC 7236 (Borne & Hoessel 1988) leads to a redshift of \( z = 0.0272 \) for 3C 442A. We adopt values for the cosmological parameters of \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.3 \), and \( \Omega_{\Lambda} = 0.7 \). Thus, 3C 442A is at a luminosity distance of 119 Mpc, and 1" corresponds to 546 pc at the source. J2000.0 coordinates are used throughout. Uncertainties are 1 \( \sigma \) for one interesting parameter unless otherwise stated.

2. OBSERVATIONS

We observed 3C 442A in VFAINT data mode with a front-illuminated CCD chip of the Advanced CCD Imaging Spectrometer (ACIS) on board Chandra. Chips I0, I1, I2, I3, and S2 were turned on for the observation, which was broken into four intervals (Table 1) and taken in full-frame mode with a readout time of 3.14 s. The data have been reprocessed with random pixelization removed following the software “threads” from the Chandra X-Ray Center (CXC). We used VFAINT cleaning and the recommended procedure of including events with status flag 5 set as bad, to preserve flux close to the CCD node boundaries and other bad pixels. This is particularly important for the third observation where NGC 7237 lies on bad pixels. Only events with grades 0, 2, 3, 4, and 6 are used in our analysis. Results presented here use CIAO version 3.3.0.1 and the CALDB version 3.2.3 calibration database.

The background count rate was steady through the four observations. Small astrometric corrections consistent with Chandra’s absolute aspect uncertainties were made to each data set to register the X-ray nucleus of NGC 7237 to the radio core whose position measured from archival 4.8 GHz Very Large Array (VLA) data and using standard AIPS procedures is 22\(^{1}\)46.808\(^{+0.002}\)\(^{-0.002}\) + \(13^h50^m27.23^s \pm 0.02^s \). The dates, durations, CCD chips in which NGC 7237 was contained, and sizes of the astrometric corrections for each observation are given

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4 See http://cxc.harvard.edu/ciao.
5 M. Markevitch 2006; ACIS background cookbook available at http://cxc.harvard.edu.
TABLE 1

| ObsID | Date       | Duration (ks) | CCD Chip | Shift (arcsec) |
|-------|------------|---------------|----------|----------------|
| 5635  | 2005 Jul 27| 27.006        | I0       | 0.495          |
| 6353  | 2005 Jul 28| 13.985        | I0       | 0.594          |
| 6359  | 2005 Oct 7 | 19.883        | I2       | 0.373          |
| 6392  | 2006 Jan 12–13| 32.694      | I0       | 0.151          |

a NGC 7237 on this chip.
b Astrometric correction to align the X-ray nucleus to the radio core in NGC 7237, mostly in declination.

in Table 1. The merged data set is of duration 93.568 ks. For spectral analysis, we created appropriate response files for the separate observations and fitted the four data sets to models in common.

To investigate the radio structure, we use 1.375 GHz VLA archival data from program AC131 (Comins & Owen 1991). For the regions around NGC 7236 and NGC 7237, we reduced the B-array data using AIPS. Our image has a 4″ FWHM restoring beam and a pixel size matched to Chandra. For the large-scale structure, we have used the smoothed version of the combined B-, C-, and D-array image of Comins & Owen (1991), which has a 7.5″ FWHM restoring beam. We have mapped the X-ray events directly onto the radio grids and applied exposure corrections before combining the images from the four Chandra observations when comparing the radio and X-ray images.

3. MORPHOLOGY

As seen from Figure 1, the dominant X-ray emission is diffuse, extending a few arcminutes and elongated in a roughly north-south direction. The high spatial resolution and high sensitivity of the Chandra data separate emission from NGC 7236 and NGC 7237 and a third galaxy in the northwest-southeast chain (see Fig. 2 for their locations). The inner X-ray-emitting gas has a distinctly higher surface brightness than larger scale emission that provides the background for the contours shown in Figure 1.

Despite the elongated nature of the X-ray distribution, a radial profile gives a good indication of the gas properties and is commonly used in the analysis of group and cluster X-ray emission. We measure the component of most interest, the emission between the radio lobes, by constructing a radial profile out to 2′ from NGC 7237, masking other discrete sources and using exposure-corrected background from a rectangular region between 3.6′ and 5.7′ to the northwest, which is observed in all four observations. The result for X-rays between 0.3 and 5 keV is shown in Figure 3. NGC 7237 is not precisely positioned at the optical aim point in the four observations, giving different point-spread functions (PSFs). For simplicity, we defer investigation of NGC 7237 (see Hardcastle et al. 2007) and use an on-axis PSF convolved with a $\beta$ model of very small core radius to fit the inner component. The outer component gives a reasonable fit to a convolved $\beta$ model with best-fit values $\beta = 0.62$, $\theta = 28.4″ (15.5 \text{ kpc})$, which is small for a normal group and much less than the scale of the group component on which this component is superimposed (Fig. 3 and Hardcastle et al. 2007).

4. GAS PROPERTIES

The temperature of the bright gas has been measured by extracting counts from a $\sim 1 \text{ arcmin}^2$ rectangular box placed within the outer contour of Figure 1 and avoiding point sources. The background region is as described in § 3. The box was first

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Fig. 1.—X-ray contours (logarithmic spacing) on a color image of the 1.4 GHz radio emission. The lowest contour is roughly at 3 $\sigma$ significance. Emission from several discrete sources is seen, including NGC 7237 and NGC 7236. Bright X-ray emission fills the gap between the lobes of 3C 442A.
NGC 7236 and NGC 7237. Contours (0.25, 0.5, 1, 2, 4, and 8 mJy beam
to see morphological evidence for the influence of the lobe on
overpressured as compared with the inner gas, we should expect
of the merger gas that has been sweeping them apart.
place north of NGC 7236 and then south of NGC 7237. The
data were fitted to an absorbed thermal model, and the parameter
values for the north and south locations were in good agreement.
No significant improvement in the fits were obtained when the
absorption was allowed to vary from the Galactic column density
of \( N_H = 5.03 \times 10^{20} \) cm\(^{-2}\) obtained from the COLDEN
program provided by the CXC and based on the data of Dickey &
Lockman (1990). The combined data from the two regions fit a
termal emission model of \( kT = 1.1^{+0.3}_{-0.1} \) keV with abundances
0.2\(^{+0.5}_{-0.1}\) of solar (1 \( \sigma \) uncertainties for two interesting parameters;
\( \chi^2 = 52 \) for 51 degrees of freedom).
We use the equations of Birkinshaw & Worrall (1993) to
de project the \( \beta \)-model X-ray surface brightness profile (containing
roughly 5000 counts out to a radius of 90") and combine it with our spectral results to form a pressure distribution.
At a radius of 1", roughly corresponding to the position of inner
contact between the gas and the radio-lobe plasma, the pressure
is \( 7.9^{+1.1}_{-1.0} \times 10^{12} \) dynes cm\(^{-2}\), where uncertainties are calculated
as described in Worrall & Birkinshaw (2001) and are
dominated by the uncertainty in the abundances. Our merger
explanation for the gas (see below) makes it likely that this is
an underestimate of the total force felt by the lobes, because the
kinetic energy density of the gas has not yet entirely dissi-
apted. The total gas mass is \((3 \pm 1) \times 10^{10} M_\odot\).

5. DISCUSSION

While the component of group gas around 3C 442A has no
usual characteristics, the extra component of inner gas is
remarkable. We believe this gas is the result of the ongoing
merger between NGC 7236 and NGC 7237 and was responsible
for disrupting what was once a rather ordinary radio galaxy
emanating from either NGC 7236 or NGC 7237. The data
support a picture in which, for about 10\(^5\) yr since the gas spheres
overlapped, the lobes have been riding on the pressure front of
the merger gas that has been sweeping them apart.

If the reverse situation applied, and the radio lobes were
overpressured as compared with the inner gas, we should expect
to see morphological evidence for the influence of the lobe on
the gas, one example being a shock, as in the southwest inner
lobe of Cen A (Kraft et al. 2003), although here with the lobes
expanding in toward the center. That is not seen. Instead, the
morphological appearance is rather of the gas separating the
radio lobes, i.e., with the inner radio contours being sharp and
concave (rather than the normal lobe case of being convex),
as is particularly clear for the west lobe (Fig. 2).

Although the pressure of the gas touching the inner edges
of the lobes is well measured by the Chandra data as \( \sim 8 \times 10^{-12} \) dynes cm\(^{-2}\), the pressure inside the lobes, which on our
interpretation cannot be higher, is more uncertain. Pressure esti-
mates in radio lobes require assumptions about the departure
from particle and magnetic field energy equipartition, filling fac-
tors, and extrapolations of the observed radio spectrum to infer
the energy of the radiating (and nonradiating) particles. Comins &
Owen (1991) estimate \( 4 \times 10^{-13} \) dynes cm\(^{-2}\) for the pressure
assuming equal energy in electrons, protons, and magnetic field
we agree). If the lobe pressure were indeed this low, then the
lobes would be underpressured even with respect to the gas
component at larger (\( \sim 2\)”) radii, evident at the extremities of the
radial profile in Figure 3, and so would be collapsing. Comins &
Owen (1991) noted the filamentary nature of the radio struc-
ture (Fig. 2), which they compared with the filamentation in the
Crab Nebula, and suggested that the internal pressure should be
raised by a factor of 4–5 once the low filling factor is taken into
account. There is much scope for raising the lobe pressure, while
still keeping it underpressured with respect to the inner gas.

In addition to the pressure-driven expansion of the gap be-
tween the lobes, we expect old radio lobes to be of low density,
and hence buoyancy could also help to separate the lobes. Since
the pressure front at the edge of the merger gas will be moving
outward at the sound speed, while buoyant motion involves large-
scale circulation that is only subsonic, we expect the inner edges
of the lobes to be defined by the pressure front around the merger
gas. The morphology of the inner edge of the west radio lobe
supports this view, since it does not resemble a buoyant plume.

We suggest that the merger between NGC 7236 and NGC
7237 created the \( \sim 1 \) keV gas envelope around the two galaxies
by heating the atmospheres of two gas-rich elliptical galaxies.
The total gas mass of \( \sim 3 \times 10^{10} M_\odot\) is rather high for the
combined galaxy gas alone and suggests a contribution from
group gas originally around one or both of NGC 7236 and
NGC 7237, as supported by the presence of the large-scale gas

![Fig. 2.—Spitzer 4.5 \( \mu \)m image showing the diffuse red envelope enshrouding NGC 7236 and NGC 7237. Contours (0.25, 0.5, 1, 2, 4, and 8 mJy beam\(^{-1}\)) are from the 1.4 GHz radio map with a 4” FWHM restoring beam and highlight the relatively sharp inner edge of the west lobe and the overall filamentary structure of the radio emission.](image1)

![Fig. 3.—The 0.3–5 keV radial profile centered on NGC 7237 with other discrete sources removed. The fit to two \( \beta \) models convolved with a nominal on-axis PSF gives \( \chi^2 = 33.6 \) for 20 degrees of freedom. The relatively poor fit for the larger scale \( \beta \) model, describing the gas between the radio lobes, is indicative of an atmosphere that is not spherical and may not have reached dynamical or hydrostatic equilibrium. The residuals at 100” point to a larger scale, lower surface brightness group gas that envelops the radio lobes (see Hardcastle et al. 2007).](image2)
component in the system (see Hardcastle et al. 2007). We note, however, that $10^{10} M_\odot$ coronae have been measured in isolated elliptical galaxies. NGC 4555 is such a case (O'Sullivan & Ponman 2004) and shows subsolar abundances as we find in 3C 442A. However, NGC 4555 is a somewhat more massive galaxy than either major galaxy in 3C 442A, with a velocity dispersion of $350 \pm 1$ km s$^{-1}$ (Wegner et al. 2003), as compared with $257 \pm 17$ and $225 \pm 31$ km s$^{-1}$ (Tonry & Davis 1981) for NGC 7236 and NGC 7237, respectively.

The sound crossing time in the gas between the lobes is $\sim 10^8$ yr. This would be the timescale on which the radio lobes are being separated by the gas between them, and it gives an approximate date for the violent phase of the merger that would have heated the gas. This is consistent with the prominent large-scale stellar merger fans (Borne & Hoessel 1988, Figs. 2 and 4; M. Birkinshaw et al. 2007, in preparation), which are typ-ically visible for 4; M. Birkinshaw et al. 2007, in preparation), which are typ-

![Image](L82.png)

**Fig. 4.—**Center of the color image of Fig. 2 with X-ray contours of the brightest emission. The gas trails to the west of NGC 7237 and northeast of NGC 7236 are noticeably misaligned with the northwest-southeast merger fans seen in the infrared.

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