X-RAY–EMITTING ATMOSPHERES OF B2 RADIO GALAXIES

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ABSTRACT

We report ROSAT PSPC spatial and spectral analyses of the eight B2 radio galaxies NGC 315, NGC 326, 4C 35.03, B2 0326+39, NGC 2484, B2 1040+31, B2 1855+37, and 3C 449, expected to be representative of the class of low-power radio galaxies. Multiple X-ray components are present in each, and the gas components have a wide range of linear sizes and follow an extrapolation of the cluster X-ray luminosity/temperature correlation, implying that there is no relationship between the presence of a radio galaxy and the gas fraction of the environment. No large-scale cooling flows are found. There is no correlation of radio-galaxy size with the scale or density of the X-ray atmosphere. This suggests that processes on scales smaller than those of the overall gaseous environments are the major influence on radio-source dynamics. The intergalactic medium is usually sufficient to confine the outer parts of the radio structures, in some cases even to within 5 kpc of the core. In the case of NGC 315, an extrapolation suggests that the pressure of the atmosphere may match the minimum pressure in the radio source over a factor of ~40 in linear size (a factor of ~1600 in pressure).

Subject headings: galaxies: active — radiation mechanisms: nonthermal — radio continuum: galaxies — X-rays: galaxies

1. INTRODUCTION

Sensitive ROSAT observations have shown that low-power radio galaxies display a mixture of X-ray emission components from a combination of processes. The dominant components are usually (1) an extended atmosphere of X-ray-emitting gas and (2) unresolved emission whose primary origin is most likely nonthermal radiation associated with the radio-emitting plasma in the innermost parts of the source (Worrall & Birkinshaw 1994; Hardcastle & Worrall 1999). The balance of these and other emission components differs from galaxy to galaxy, and each source must be observed in detail in order to disentangle the emission processes and probe the physics.

The X-rays associated with the most compact active regions of radio galaxies are likely to originate not only as emission from the inner jets, which are affected by relativistic beaming, but also as more isotropically emitted radiation produced even closer to the central engine of the active galactic nucleus (AGN). Since radio galaxies do not shine as brightly in compact X-ray emission as Seyfert galaxies and quasars, this AGN component is suppressed as a result of either the low radiative efficiency of accretion-related thermal emission, or asymmetric obscuration. In the latter case, the AGN’s contribution to the compact emission should increase toward higher X-ray energies. If models of source unification are to be addressed in the X-ray, the extended nonnuclear emission must be measured and removed to reveal the uncontaminated nuclear properties of the active galaxy.

The existence of an extended X-ray–emitting medium is probably essential for prominent radio jets to develop, but finding trends in the morphology of radio structures with gas density and distribution requires studies of the atmospheres on a source-by-source basis. Excluding roughly the inner kiloparsec, it seems in general that the external medium supplies more than enough pressure to confine the radio jets of low-power radio galaxies, assuming a jet pressure calculated using minimum-energy arguments (e.g., Morganti et al. 1988; Killeen, Bicknell, & Ekers 1988; Feretti et al. 1995; Trussoni et al. 1997). In some cases, an apparent evacuation of the external medium within the jets argues that additional jet pressure is required and must be supplied by something other than thermal material (e.g., Böhringer et al. 1993; Hardcastle, Worrall, & Birkinshaw 1998). Such “light” jets should then be affected by buoyancy forces (e.g., Worrall, Birkinshaw, & Cameron 1995), and it is of interest to examine how morphological features, such as the disruption of jets into lobe emission, map onto abrupt or gradual changes in the X-ray–emitting environment. In exceptional cases, it appears that relatively low powered jets on scales of tens to hundreds of kpc remain overpressured with respect to the external medium (e.g., Birkinshaw & Worrall 1993).

The X-ray–emitting medium may play an important role in fueling the central engine, particularly if it is involved in a cooling flow that continues into the nuclear regions. However, observations with excellent spatial resolution are needed to distinguish the central part of a cooling flow from the smaller scale emission associated with the inner radio jets or the AGN itself.

This paper presents a thorough analysis of eight low-power radio galaxies using the best available X-ray data. In § 2 we describe the selection of sources, the extent to which they are representative of their parent B2 galaxy sample, and the ROSAT observations. Sections 3 and 4 describe the spatial and spectral distributions of the X-ray emission. In § 5 we discuss the physical characteristics of the X-ray–emitting environments and how their pressures compare with those of the kiloparsec-scale radio jets. Section 6 discusses in more detail the giant radio source NGC 315, whose X-ray emission is the most compact among the sample objects. The Appendix gives notes and comparisons with previous X-ray work for the other seven radio galaxies of the sample. Our conclusions are summarized in § 7.
Throughout the paper, we adopt a Friedmann cosmological model with $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$.

2. SAMPLE SELECTION AND X-RAY EXPOSURES

The complete subset of 50 sources from the B2 radio survey identified with elliptical galaxies brighter than $m_{\text{ph}} = 15.7$ (Colla et al. 1975; Ulrich 1989) is the largest unbiased sample of exclusively low-power radio galaxies studied with sensitive pointed X-ray observations to date. Forty of the sources were observed in ROSAT pointings, half by us through various announcements of opportunity as, taking into account sources observed by others, we defined subsamples with increasingly broader selection criteria, so that the largest possible and least biased subset was observed at any one time. Following the demise of ROSAT in 1999 February, a summary of the X-ray results for the sample was prepared and appears in Canosa et al. (1999), which also refers to published detailed work by us and others for some of the individual objects.

Most B2 sample sources were observed with the ROSAT High Resolution Imager (HRI), but earlier in the mission observations could be made with the Position Sensitive Proportional Counter (PSPC), which, while having a poorer spatial response than the HRI, had spectral capabilities and was more sensitive to faint, diffuse X-ray structures.¹

We observed eight sample members (Table 1) with the PSPC, four of which (NGC 315, 4C 35.03, NGC 2484, and 3C 449) were also observed later with the ROSAT HRI by us or others in order to probe in greater detail the nuclear part of the structure. Figure 1 plots histograms of redshift, absolute $V$-band galaxy magnitude, and 408 MHz radio power for the complete subsample of the 47 out of 50 B2 sample objects with $z \leq 0.065$, indicating with solid shading.¹

1 See the ROSAT Users Handbook, available at: http://heasarc.gsfc.nasa.gov/docs/rosat/ruh/handbook.

### TABLE 1

| B2 Name | Other Name | $z$ | $N_{\text{H}}$ (10^{20} \text{ cm}^{-2})$ | $\text{kpc/arcmin}^b$ | $\text{LAS}^c$ (arcsec) | Reference |
|---------|------------|----|----------------------------------|-----------------|-----------------|------------|
| 0055+30...... | NGC 315 | 0.0165 | 5.77 | 28 | 3650 | 1 |
| 0055+26...... | NGC 326 | 0.0472 | 5.47 | 77 | 150 | 2 |
| 0206+35...... | 4C 35.03 | 0.0375 | 5.90 | 62 | 89 | 3 |
| 0326+39...... | NGC 2484 | 0.0243 | 14.21 | 41 | 340 | 2 |
| 0755+37...... | NGC 315 | 0.0413 | 5.02 | 68 | 138 | 3 |
| 1040+31...... | 3C 449 | 0.036 | 1.82 | 60 | 54 | 3 |
| 1855+37...... | 3C 449 | 0.055 | 8.01 | 89 | 10 | 3 |
| 2229+39...... | 3C 449 | 0.0171 | 11.05 | 29 | 840 | 2 |

* From Stark et al. 1992.

$^b$ $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0$.

$^c$ Largest angular size of the radio structure.

REFERENCES.—(1) Bridle et al. 1979; (2) Ekers et al. 1981; (3) Fanti et al. 1987.

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![Fig. 1](image-url)---

Fig. 1.—Histograms of redshift, absolute $V$-band galaxy magnitude (Ulrich 1989), and 408 MHz radio power (Colla et al. 1975, corrected to the flux scale of Baars et al. 1977) for the complete sample of 47 B2 radio galaxies with $z \leq 0.065$ (Canosa et al. 1999). Solid shading shows that the subset of eight sources in this work are representative of the complete sample in all three properties except total radio power.
the eight sources discussed in the present paper. Only in absolute radio power are the eight observed sources unrepresentative of the sample as a whole, being biased toward high power: a Kolmogorov-Smirnov test gives a probability of only ~3% of the subsample being drawn at random in radio power, whereas similar tests for redshift and galaxy magnitude give probabilities of greater than 60%. This bias in total radio power was unintentional, but most likely occurs through our placement of sources with better radio data at higher priority for X-ray observation. For our observations we also avoided sources in known clusters (several B2 radio galaxies are in Abell clusters), although this was a priority for other observers. Six of the sources had no previous X-ray observations, and two had been observed with the Einstein Observatory: NGC 315 is reported as unresolved and variable at 3σ significance between two observations separated by about 7 months (Fabbiano, Kim, & Trinchieri 1992), whereas the emission from 3C 449 was resolved by the Imaging Proportional Counter (Miley et al. 1983). Only three other B2 bright-sample radio galaxies that are not in the Coma Cluster or an Abell cluster have on-axis exposures of more than 5 ks with the ROSAT PSPC, and all exhibit extended X-ray emission: 3C 31 (Trussoni et al. 1997; Komossa & Böhinger 1999), NGC 507 (Kim & Fabbiano 1995), and NGC 3665 (Massaglia et al. 1996).

Dates and exposure times for the PSPC observations reported here are given in Table 2, along with net counts within a radius large enough to incorporate most of the extended emission. Earlier reports on some aspects of these data for five of the sources appear in Worrall & Birkinshaw (1994), Worrall et al. (1995), and Hardcastle et al. (1998). A discussion of the extended emission in 0326+39, 1040+31, and 1855+37 has not appeared elsewhere. In this paper we present results derived in a consistent fashion for the gaseous X-ray-emitting environments of all eight sources, and we compare these environments and discuss their relationships to the radio structures that they host.

The observations of NGC 315 were split into two observing periods separated by 6 months. Because of the reported variability in the Einstein data, and in order to measure the level of likely systematic error in our analysis procedures, we treated the two exposures separately for much of the analysis. The fluxes measured in the two exposures are in good agreement (Table 2) and do not confirm the earlier reports of variability.

3. SPATIAL DISTRIBUTION OF X-RAY-EMITTING GAS

X-ray images of all eight sources are presented in Figures 2 and 3. For these images, the Extended Source Analysis Software (EXAS) of Snowden (1995) was used to model and subtract background components and correct for exposure and vignetting, except for NGC 326, for which we used an earlier procedure based on IRAF/Post Reduction Off-line Software (PROS) tools that was found to give similar results (Worrall et al. 1995). The adaptive smoothing technique described by Worrall et al. (1995) has been applied to all the images in order that the display should distinguish clearly between unresolved sources and diffuse emission. The PSPC point response function (PRF) increases at off-axis angles, as is evident in the images. Extended emission is seen around all the radio galaxies, which lie in the center of the fields. The angular extent is not anticorrelated with luminosity distance, as would be expected if the radio galaxies were in environments of similar spatial scale.

Although asymmetries are evident in the gas distributions, the construction of a radial profile, after subtraction of emission from contaminating unresolved sources, is a useful tool for characterizing with a small number of parameters the spatial distribution of gas. It is a reasonably robust way of separating unresolved emission associated with the radio galaxy, and the models can be extrapolated to radii where emission no longer lies significantly above the level of the background, in order to get the best possible measurement of the total luminosity of the source. Compared to Worrall & Birkinshaw (1994) and Canosa et al. (1999), the on-source extractions used in our radial profiles

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**TABLE 2**

| Source          | Dates         | ROR*   | Exposureb (s) | Radius (arcmin) | Net Counts* |
|-----------------|---------------|--------|---------------|-----------------|-------------|
| NGC 315         | 1992 Jan 17–Feb 1 | 700424 | 10343         | 3               | 500 ± 28    |
|                 | 1992 Jul 19–21 | 700424 | 17869         | 3               | 865 ± 37    |
|                 | total          | 700424 | 29626         | 3               | 1430 ± 63   |
| NGC 326         | 1992 Jul 24–29 | 700884 | 19409         | 6               | 1066 ± 42   |
| 4C 35.03        | 1992 Jul 24–27 | 700316 | 14843         | 6               | 512 ± 41    |
| 0326+39         | 1993 Aug 15–25 | 701442 | 18931         | 5               | 933 ± 65    |
| NGC 2484        | 1991 Oct 30–Nov 1 | 700315 | 15172         | 3               | 523 ± 36    |
| 1040+31         | 1993 May 10–21 | 700883 | 21952         | 6               | 1492 ± 68   |
| 1855+37         | 1993 Sep 27–28 | 701445 | 8771          | 8               | 3216 ± 80   |
| 3C 449          | 1993 Jan 4–10  | 700886 | 9151          | 10              | 1774 ± 74   |

* ROSAT Observation Request number.

b Lifetime used in analysis. May be shorter than in the distributed files due to additional screening for high background.

0.2–1.9 keV in source-centered circle of radius given in col. (5), after areas of any contaminating point sources have been removed from on-source and background regions. For NGC 326, counts at radii greater than 3′ are for position angles 125°–290° only, i.e., region of least extent.

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2 EXAS is available at: ftp://legacy.gsfc.nasa.gov/rosat/software/fortran/xsrb.
are generally to larger radii, to allow a better description of the falloff of gas with radius and a more precise determination of gas temperature. The fitting is therefore less good at characterizing the properties of compact, unresolved, emission. Several faint, nearby, contaminating, unresolved sources were defined by eye as localized excesses, and regions of typically 1'-2.5' in radius enclosing them were excluded from the on-source and background areas for both structural and spectral analyses.

Single-component $\beta$ models\(^3\), describing gas in hydrostatic equilibrium (e.g., Sarazin 1986), and a combination of $\beta$-model and unresolved emission have been convolved with the energy-dependent PRF and fitted to the radial profile for each source. Only counts within the energy band for which the PRF is well modeled (0.2-1.9 keV)\(^4\) are used in the spatial analysis. In contrast to Worrall & Birkinshaw (1994), who assumed $\beta = 2/3$, fits were performed for a range of $\beta$ between 0.35 and 0.9. In general, results are fairly insensitive to $\beta$, but the values of $\beta$ and the core radius, $\theta_{cx}$, are highly correlated, as shown in Figure 4, making FWHM a better indicator of spatial extent than $\theta_{cx}$. Radial profiles and the best-fit models are given in Figure 5, and parameter values are listed in Table 3. All profiles are significantly improved by the inclusion of nuclear unresolved emission, except perhaps for NGC 315. In most sources the fraction of counts in this unresolved emission is relatively small, largely due to a large on-source extraction radius.

\(^3\) Counts per unit area per unit time described by $B_0[1 + (\theta^2/\theta_{cx}^2)^{0.5-3\beta}]$

\(^4\) See the ROSAT Users Handbook, available at: http://heasarc.gsfc.nasa.gov/docs/rosat/ruh/handbook.
4C 35.03, NGC 2484, and 3C 449 were also observed with the HRI (see notes in the Appendix). In each case, the amount of nuclear unresolved flux as measured with the PSPC matches that measured with the HRI, and so we can conclude that the compact component is more peaked and of angular size a factor of 3–4 times smaller than the PSPC PRF shown in Figure 5. The more complicated case of NGC 315 is discussed in § 6.

4. THE X-RAY SPECTRA

Spectral fits to the data were carried out over the full energy range of the PSPC, and results are given in Table 4. For sources for which the spatial fitting gives ≥ 14% of the counts in a central component, we have attempted a two-component (thermal plus power law) spectral fit. The relative numbers of counts in the two components are generally less well constrained than in the radial-profile component separation; results in column (5) of Table 4 (expressed only over the energy band 0.2–1.9 keV for consistency with the spatial separation) can be compared with column (2) of Table 3. Best-estimate fluxes, luminosities (Table 4), and temperatures (Table 5) for the thermal gas are interpolated from the single-component and two-component fits. Spectral fits assume that the only absorption is due to gas in the line of sight in our Galaxy, and we have fixed the abundances at 30% solar, consistent with results for more luminous clusters. The abundance fraction is fairly poorly constrained by the PSPC data, particularly for two-component fits. However, for all sources the best fit is for ≤ 40% solar, and fits with 100% solar abundances give values of $\chi^2$ more than 2.7 larger than $\chi^2_{min}$, indicating that they are unacceptable at greater than 90% confidence. Although the PSPC's spectral resolution is relatively poor, the peak response is well matched to the temperatures found for the gaseous distributions around these radio galaxies.
5. CHARACTERISTICS OF THE RADIO-GALAXY ENVIRONMENTS

In Figure 6 we compare the bolometric luminosity and temperature of the X-ray-emitting gas around each radio galaxy to the extrapolated but well-constrained luminosity-temperature ($L_{bol}-kT$) relation for more luminous clusters (with $kT > 2$ keV) from Arnaud & Evrard (1999). Agreement is good. Since X-ray luminosity is governed by the gas mass, while the temperature is determined by the total gravitating mass, the result implies that there is no relationship between the presence of a radio galaxy and the gas fraction of the environment. This is an interesting point, since the X-ray gas may play a role in the fuelling of radio galaxies, particularly in the presence of cooling flows. However, as seen from Table 5, NGC 315 is the only source with a central cooling time that is much less than the Hubble time, and this is the only source for which the gas distribution is of galaxy size rather than cluster (or group) size. There is no evidence in the present data for cluster-scale cooling flows.

Radio-source size is not correlated with the size of the X-ray-emitting medium (Fig. 7); note that the FWHM (Table 3) is a scale factor for the size of the X-ray-emitting medium rather than its total (much larger) extent. The lack of a correlation is perhaps not surprising, given that the
sound crossing time in X-ray gas 10–100 kpc in extent, at \( \sim (20–200)(kT/\text{keV})^{-1/2} \) Myr, is comparable to typical radiative ages of low-power radio galaxies, at 10–100 Myr (Parma et al. 1999), and so only for the oldest sources might it be expected that the gas has had time to adjust to the presence of the radio galaxy. Conversely, the lack of correlation suggests that it is small-scale processes, on size scales less than those of the overall gaseous environments, that are the major influence on radio-source dynamics and propagation.

As the spatial resolution of X-ray measurements improves, it is not surprising that the inferred central gas densities decrease, as gas is resolved into larger regions. Morganti et al. (1988) infer significantly higher central densities than our values (Table 5) for a subsample of B2 radio galaxies measured with Einstein, although none of the objects is in common with sources in this work. Moreover, they tentatively claim an anticorrelation between the largest linear extent of a radio source and central gas density, interpreting this to be evidence that the gas has a direct influence on the morphology of the radio source. No such anticorrelation is evident in our results (Fig. 8), and again this can be understood in terms of the long timescale for X-ray gas to react to the influence of a radio source.

For all the sources, we have compared minimum pressures in various parts of the radio structures with the pressure from the X-ray gas. For the radio pressure calculations, it was assumed that the synchrotron spectrum extends above 50 MHz, that the electron energy spectrum is of \( E^{-2} \) form, and that electrons and protons contribute equally to the internal energy. Results for six of the sources are given in Figure 9, and individual notes appear in the Appendix and § 6.

Within the limitations of the available radio-mapping data, the diffuse outer parts of all eight radio sources exhibit minimum pressures close to or below the local pressures implied by the best-fit X-ray atmospheres. In the inner parts of the sources, where strong jets are seen, the minimum pressures in the kiloparsec-scale structures sometimes lie above the pressure of the ambient gas. Thus, if we are to believe that the radio structures are in pressure equilibrium with the external medium, we require that at small angles
from the cores there should be an additional confinement mechanism, while at large angles from the cores additional internal pressure is needed. There are several mechanisms for additional internal or external pressure. By definition, the minimum pressures are likely to be underestimated, with higher true pressures likely if the sources have substructure, contain a large population of nonradiating relativistic particles or entrained ambient material (on which limits can be placed by depolarization studies if the magnetic field has a simple topology), or are simply far from equipartition. If the sources are not in the plane of the sky, then projection effects tend to overestimate the local ambient pressures. Additional external confinement might be provided by magnetic fields or local pressure enhancements near the radio sources and associated with the source dynamics.

There are three exceptions to this general pattern. 3C 449 and 4C 35.03 are underpressured over their entire structures, and NGC 315 may remain close to pressure equilibrium throughout its length. NGC 315 is 1.7 Mpc in size, easily the largest in our sample, and here an extrapolation beyond the region of clear X-ray detection suggests that the source may remain close to pressure equilibrium over a factor of 1600 variation in the ambient gas pressure. We would speculate that it is because NGC 315 is close to

**TABLE 3**

**Best-fit Two-Component Models to the Radial Profiles**

| Source      | $C_C/C^*$ | FWHM$^a$ | $\beta$  | $\theta_C$ | $\chi^2$/dof | $P(1, \text{dof})^a$ | $P_{\beta}(1, \text{dof})^b$ |
|-------------|-----------|----------|---------|-----------|-------------|----------------|-------------------|
| NGC 315     | 0.09 ± 0.06 | 20.0$^\pm$13$^b$ | 0.9 | 35 | 14.3/13 | 3.6 | 0.08 |
|             | 0.46 ± 0.05 | 7.3$^\pm$1 | 0.67 | 10 | 13.9/13 | 2.5 | 0.14 |
|             | ... | 4.3 ± 0.5 | 0.67 | 6 | 14.6/14 | ... | ... |
| NGC 326     | 0.06 ± 0.01 | 417$^\pm$40$^d$ | 0.9 | 267 | 9.4/7 | 24.8 | 0.002 |
| 4C 35.03    | 0.18 ± 0.03 | 99.8 ± 33 | 0.35 | 30 | 7.1/10 | 19.2 | 0.001 |
| 0326 + 39   | 0.14 ± 0.02 | 130.5 ± 53 | 0.35 | 60 | 11.8/17 | 43.3 | <0.001 |
| NGC 2484    | 0.65 ± 0.06 | 193.8$^\pm$110 | 0.9 | 140 | 12.4/12 | 8.7 | 0.01 |
| 1040 + 31   | 0.10 ± 0.01 | 104.8$^\pm$69 | 0.4 | 40 | 14.3/22 | 10.9 | 0.003 |
| 1855 + 37   | 0.02 ± 0.01 | 270.8 ± 33 | 0.7 | 19.3/20 | 22.1 | <0.001 |
| 3C 449      | 0.02 ± 0.01 | 61.2 ± 23 | 0.35 | 40 | 7.5/12 | 8.9 | 0.01 |

Note.—Best-fit values for 0.35 $\leq \beta \leq$ 0.9. The terms $\beta$ and $\theta_C$ are highly correlated, and so uncertainties are not given, but can be deduced from Figure 4.

$^a$ Ratio of counts in nuclear unresolved component to the total. $1\sigma$ statistical uncertainties.

$^b$ FWHM of $\beta$-model component, $2\sigma_{\beta} [2^{\pm0.8} - 1]^{1/2}$. There are 90% uncertainties for one interesting parameter.

$^c$ F statistic, which tests the improvement of adding the unresolved emission to a $\beta$ model alone.

$^d$ Random probability of exceeding $F$.

$^e$ Results for January, July, and combined data listed separately.

$^f$ Extended emission very asymmetric; results are for the direction of least extent (see Worrall et al. 1995 for details).

**TABLE 4**

**Raymond-Smith Thermal Spectral Parameters**

| Source      | $kT$ (keV) | Norm$^a$ | $\chi^2$/dof | $f^b$ | $kT$ (keV) | Norm$^a$ |
|-------------|------------|----------|--------------|------|------------|----------|
|             | (1)        | (2)      | (3)          | (4)  | (5)        | (6)      |
| NGC 315     | 0.91$^{+0.04}_{-0.03}$ | 7.5$^{+0.6}_{-0.4}$ | 49.9/30 | 0.39$^{+0.16}_{-0.09}$ | 0.62$^{+0.09}_{-0.09}$ | 3.44$^{+0.59}_{-0.56}$ | 20.2/28 |
| NGC 326     | 1.9$^{+0.9}_{-0.4}$ | 40.0$^{+1.6}_{-1.3}$ | 25.3/29 | ... | ... | ... | 3.0 | 0.54 ± 0.2 |
| 4C 35.03    | 1.4$^{+1.3}_{-0.3}$ | 7.6$^{+0.9}_{-0.6}$ | 27.2/30 | 0.6$^{+0.39}_{-0.1}$ | 1.0$^{+0.8}_{-0.5}$ | 2.43$^{+5.8}_{-2.35}$ | 26.2/28 |
| 0326 + 39   | 1.02$^{+0.12}_{-0.11}$ | 11.6$^{+1.3}_{-1.0}$ | 23.0/22 | 0.48$^{+0.34}_{-0.32}$ | 0.84$^{+0.36}_{-0.32}$ | 4.8$^{+6.7}_{-3.1}$ | 20.2/20 |
| NGC 2484    | 1.02$^{+0.15}_{-0.12}$ | 5.3$^{+0.9}_{-0.8}$ | 30.0/29 | 0.64$^{+0.29}_{-0.23}$ | 0.73$^{+0.32}_{-0.45}$ | 1.46$^{+2.34}_{-1.07}$ | 21.1/27 |
| 1040 + 31   | 1.21$^{+0.16}_{-0.11}$ | 10.9$^{+0.8}_{-0.9}$ | 29.6/30 | ... | ... | ... | 1.8 | 1.9 ± 0.2 |
| 1855 + 37   | 2.16$^{+0.41}_{-0.39}$ | 9.1$^{+1.2}_{-1.0}$ | 25.2/26 | ... | ... | ... | 26 | 6.8 ± 0.3 |
| 3C 449      | 1.15$^{+0.08}_{-0.09}$ | 46.9$^{+3.8}_{-3.6}$ | 21.7/30 | ... | ... | ... | 97 | 7.3 ± 0.3 |

Note.—Fits assume Galactic $H_T$ and abundances of 0.3 solar. Errors in $kT$ and $\text{EM}/4\pi D_L^2$ correspond to $\chi^2 + 2.3$ (i.e., 1 $\sigma$ for two interesting parameters). For NGC 326, results exclude the central excess and are taken from Worrall et al. (1995). For sources where spatial fitting gives $\geq 14\%$ of the counts in a central component, we investigate how the thermal parameters are affected by a power-law component is included. Flux and luminosity are the best overall estimates for the total thermal component. The $1\sigma$ error on the luminosity combines in quadrature the statistical error and that arising from the uncertainty in the fraction of unresolved emission. While it does not take into account an uncertainty in the correction for flux beyond the on-source extraction region, made using the best-fit core radius and $\beta$ (or $\beta = 2/3$ and the corresponding best-fit core radius if $\beta_{\text{best}} \leq 0.5$).

$^a$ EM is the volume-weighted emission measure $(\rho \pi D_L^2)^{1/2}$, and $D_L$ is luminosity distance.

$^b$ Best-fit fraction of 0.2–1.9 keV counts in the power law (error $\sim 90\%$ confidence).
### TABLE 5

| Source          | \(B_0\) (counts arcmin\(^{-2}\) ks\(^{-1}\)) | \(\beta\) | \(r_\text{ex}\) (kpc) | \(kT\) (keV) | \(n_{p,0}\) (cm\(^{-3}\)) | \(P_0\) (dynes cm\(^{-2}\)) | \(\tau_{\text{cool},0}\) (yr) |
|-----------------|------------------------|--------|-----------------|--------|-----------------|-----------------|-----------------|
| NGC 315         | 172 ± 11               | 0.67   | 4.7             | 0.62\(^{+0.09}_{-0.1}\) | 3.5 \times 10^{-2} | 7.7 \times 10^{-11} | 6.8 \times 10^{8} |
| NGC 326         | 2.0 ± 0.05             | 0.9    | 343             | 1.9\(^{+0.2}_{-0.1}\) | 7.3 \times 10^{-4} | 5.0 \times 10^{-12} | 5.7 \times 10^{10} |
| 4C 35.03        | 3.7 ± 0.3              | 0.35   | 31              | 1.3\(^{+0.3}_{-0.4}\) | 2.0 \times 10^{-3} | 9.6 \times 10^{-12} | 1.7 \times 10^{10} |
| 0326 + 39       | 3.9 ± 0.2              | 0.35   | 41              | 0.95\(^{+0.32}_{-0.3}\) | 1.8 \times 10^{-4} | 6.6 \times 10^{-12} | 1.7 \times 10^{10} |
| NGC 2484        | 1.5 ± 0.2              | 0.9    | 159             | 0.73\(^{+0.45}_{-0.4}\) | 6.4 \times 10^{-4} | 1.7 \times 10^{-12} | 4.0 \times 10^{10} |
| 1040 + 31       | 7.0 ± 0.3              | 0.4    | 40              | 1.21\(^{-0.11}_{+0.1}\) | 2.3 \times 10^{-3} | 1.0 \times 10^{-12} | 1.4 \times 10^{10} |
| 1855 + 37       | 17.5 ± 0.4             | 0.4    | 104             | 2.16\(^{+0.0}_{-0.4}\) | 2.9 \times 10^{-3} | 2.3 \times 10^{-11} | 1.5 \times 10^{10} |
| 3C 449          | 10.0 ± 0.3             | 0.35   | 19              | 1.14\(^{+0.09}_{-0.08}\) | 4.4 \times 10^{-3} | 1.8 \times 10^{-11} | 7.4 \times 10^{9}  |

**Note.**—Based on \(\beta\)-model component only. The model normalization, \(B_0\), is converted to physical quantities by convolving a thermal spectrum (with temperature given in col. [5] and based on Table 4) with the instrument response. Density and pressure decrease with radius from the tabulated central values as \(1 \propto r^{-2}\), proportional to \(1/\text{density}\). Multiply pressure values by 0.1 to give in units of N m\(^{-2}\) (Pascals). The result for NGC 315 is the best based on both epochs of PSPC data.

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**Fig. 6.**—Luminosity (from Table 4, but with bolometric corrections applied) vs. temperature (from Table 5). The open circle shows the result for NGC 315 assuming no power-law component. The solid and dashed lines show the best-fit relation and rms deviations, respectively, for more luminous clusters (\(\sim 10^{44} - 10^{46}\) ergs s\(^{-1}\)) from Arnaud & Evrard (1999).
pressure equilibrium that it is able to grow to such a large scale. The detected X-ray-emitting atmosphere extends only to \(70 \text{ kpc}\), however. Thus, it is not certain that the extrapolated X-ray pressure estimates at the largest scale of the source are realistic.

6. THE SPECIAL CASE OF NGC 315

The spatial structure of the X-ray emission around NGC 315 is unique among the sample in its compactness. Canosa et al. (1999) attributed all the (mildly extended) \textit{ROSAT} HRI flux within an on-source extraction radius of 50' to unresolved emission of luminosity \((1.3 \pm 0.1) \times 10^{42} \text{ ergs s}^{-1}\) (statistical errors), because of limitations due to the aspect-correction errors in the \textit{ROSAT} Standard Analysis Software System (SASS) data. However, the PSPC data show that extended emission is definitely present (Fig. 5), and the nature of the most compact regions of the source need further investigation.

Although the PSPC spatial analysis prefers the presence of a point source with only marginal significance (and not at all when the two observations are combined), a substantial AGN-related contribution to the PSPC data seems justified, since:

1. There is a significant improvement in spectral fits when a power-law component is included (Table 4).
2. A two-temperature thermal fit (assuming 30\% cosmic abundances) gives 56\% of the counts in a thermal of temperature 0.6 keV, and the rest in a hot component of 2.8 keV, in which case the temperature is surprisingly high, given the emission's compactness and luminosity (Fig. 6).
3. The presence of significant power-law emission is suggested by the relatively strong radio core and the correlation of radio-core and compact X-ray luminosity shown by the larger sample of B2 radio galaxies, including NGC 315 (Canosa et al. 1999).

However, the luminosity in unresolved emission from the PSPC spectral (and spatial) fitting, at \(~0.5 \times 10^{42} \text{ ergs s}^{-1}\), is significantly smaller than the total luminosity in the HRI data, and roughly equal to the contribution from gas measured with the PSPC. This suggests that the unresolved emission increased by a factor of up to 2 (depending on the precise contribution of thermal emission to the HRI flux) in the 2 yr separating the PSPC and HRI observations. This is not impossible if the emission is nonthermal and radio-related in nature, and the result is supported by the earlier \textit{Einstein} report of variability.

We have reexamined the HRI data for spatial extent after first applying software just released to approximately correct the effects of a recently identified programming error in the SASS aspect-correction software (Harris 1999). The result is that the HRI data still give an unacceptable fit to the nominal PRF, and prefer a single-component \(\beta\) model, but of very small core radius \((\theta_{\text{core}} = 3' , \beta = 2/3)\), inconsistent with the PSPC data. The extent of residual aspect errors is uncertain, but broadening the PRF by a few arcseconds results in a combination of a point source and \(\beta\) component being the preferred model, and brings the results into closer agreement with those from the PSPC data.

A further complication is that this is the only source from the current sample in which the cooling time is sufficiently short (Table 5) to suggest the presence of a cooling flow. However, although the cooling time is estimated to equal the Hubble time at a radius of \(~20 \text{ kpc}\), there is no abrupt steepening in the PSPC radial profile at such a radius (Fig. 5), as might be expected from the onset of a cooling flow. If for the HRI data a single-component cooling-flow model fit (of the type described in Hardcastle, Worrall, & Birkinshaw 1999) is attempted, then no improvement over a point-source plus \(\beta\) model is achieved unless the cooling radius of the gas is \(~5 \text{ kpc}\), which not only implies an atmosphere less than \(~300 \text{ Myr}\) old, but is also inconsistent with the larger cooling radius suggested by the PSPC data. It certainly remains a possibility that a very small scale cooling

![Graph](image-url)
FIG. 9.—Thermal pressures in the atmosphere of NGC 315, NGC 326, 4C 35.03, B2 0326 + 39, NGC 2484, and 3C 449 as deduced from fits to the X-ray images (solid line; line is dashed where extrapolated beyond region of clear X-ray detection), compared with minimum internal pressure estimates (horizontal bars, which indicate the range of angles over which the pressure estimates apply). The internal pressures are based on maps from Willis & O'Dea (1995, private communication) and estimates from Mack et al. (1998) for NGC 315; 1.4 and 4.9 GHz maps from Worrall et al. (1995) for NGC 326; pressures from Parma et al. (1986) for 4C 35.03; pressures from Bridle et al. (1991) for B2 0326 + 39; an unpublished 4.9 GHz map from Birkshaw & Davies for NGC 2484; and pressures from Hardcastle et al. (1998) for 3C 449.
flow contributes to the unresolved emission, and we now await data from the Chandra Observatory, whose ~0.5" resolution will significantly improve our knowledge of the inner regions of this source.

The minimum pressures of various regions in the inner radio jet of NGC 315 were estimated from a 1.4 GHz WSRT map kindly provided by Alan Willis, and supplemented by the lower resolution results of Mack et al. (1998) in the outer parts of the source. Figure 9 shows these minimum pressures superimposed on the pressure of the X-ray-emitting atmosphere estimated from the best-fitting β model (Table 5) and extrapolated beyond the regions of clear X-ray detection. This figure suggests that if the radio jet lies close to the plane of the sky, then only the knot at about 5′ from the core may lie significantly out of pressure balance; all the other parts of the jet and the outer radio source may lie near pressure equilibrium or be confined by the external medium. Given the wide range in pressures (a factor of 1600), this suggests that the structure of NGC 315 may be strongly influenced by the X-ray-emitting atmosphere over the entire region outside 20′ from the nucleus. Within 20′ of the nucleus, the radio data available to us have insufficient resolution to allow a useful estimate of the minimum pressure; similarly, structures of smaller angular size in other parts of NGC 315 may be far from pressure balance.

Figure 10 shows an overlay of the inner part of the radio source on the PSPC X-ray emission. There is a possible small-scale extension of the X-ray emission along both jets, but the two X-ray excesses to the northwest, one of which lies on the jet, are most likely associated with background sources for which optical candidates are visible on the Palomar Sky Survey images.

7. CONCLUSIONS

The analyses of these eight B2 radio galaxies lead to several conclusions that we expect to be generic of low-power radio galaxies as a class:
1. All eight X-ray sources exhibit multiple components.
2. The extended atmospheres have a wide range of linear sizes, and follow the cluster X-ray luminosity/temperature correlation.
3. No large-scale cooling flows are found, although a small-scale cooling flow may be present in NGC 315.
4. There is no correlation of radio-source size with the scale or density of the X-ray atmosphere, suggesting that processes on scales less than those of the overall gaseous environments are the major influence on radio-source dynamics.
5. The outer parts of the radio sources are usually pressure-confined by the X-ray atmospheres, if they are close to minimum energy.

6. For NGC 315, an extrapolation of the pressure of the atmosphere suggests that pressure balance may be maintained over a factor of ~1600 in gas pressure and an overall size of ~1.5 Mpc, although the detected X-ray gas has a FWHM of only ~5 kpc. Deeper X-ray images are needed to test this possibility.

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APPENDIX

NOTES ON INDIVIDUAL SOURCES

NGC 315.—This source is discussed in detail in § 6.

NGC 326.—Further results based on the ROSAT PSPC observation appear in Worrall et al. (1995), including an interpretation of the strongly distorted radio structure as being due to a buoyant backflow of radio plasma in the X-ray-emitting medium. The spectroscopy of cluster galaxies of Werner, Worrall, & Birkinshaw (1999) gives a velocity dispersion that is consistent with expectations from the X-ray–derived cluster properties. The minimum radio pressures presented in Figure 9 were estimated from the low-resolution 1.4 GHz radio map and higher resolution 4.9 GHz maps described by Worrall et al. (1995). The inner radio jets appear to be close to pressure balance with the X-ray gas, while the outer parts of the source appear underpressured, in accordance with the usual pattern (§ 5).

4C 35.03.—The ROSAT HRI data are consistent with an unresolved source of luminosity $10^{42}$ erg s$^{-1}$ (Canosa et al. 1999), which is about 25% that of the thermal gas (Table 4) and in good agreement with the fraction of unresolved emission in the PSPC radial profile (Table 3). The radial profile is relatively insensitive to the value of $\beta$, but prefers a flatter distribution than $\beta = 2/3$, which was assumed by Worrall & Birkinshaw (1994). The unresolved X-ray emission appears not to be a smooth continuation of the extended gas; it may be predominantly either a galaxy-scale atmosphere (Trussoni et al. 1997), in which case it would be cooling rapidly, or a point-source component associated with the active nucleus. The latter interpretation is favored here. Our approved Chandra observation should settle this matter. The radio appearance of the source has been described by Fanti et al. (1986); it exhibits small ($\approx 20^\circ$) jets to either side of the core, embedded in a roughly elliptical halo of lower brightness emission. The minimum radio pressures in the jets and the halo, as calculated by Parma et al. (1986), are a factor of 4 or more below the pressure of the X-ray–emitting atmosphere, indicating that the source is likely to be well-confined by the external gas. This may account for the sharp edges of the radio image, and suggests that even the inner radio jets’ dynamics are strongly affected by the gas environment.

0326 + 39.—In Canosa et al. (1999), our spatial decomposition of the PSPC data uses a smaller on-source region to probe the unresolved X-ray component. There are no ROSAT HRI observations of this source. The source was mapped in detail at radio frequencies by Bridle et al. (1991), and the minimum pressures in the jets shown in Figure 9 are taken from Figure 14 of that paper (adjusted to our choice of $H_0$). It can be seen that the jets are overpressured relative to the X-ray gas within about $20^\circ$ of the core, and underpressured thereafter. This angle from the core marks an abrupt transition in the radio image, where the jets decrease suddenly in brightness. It can be seen that this does not correspond to any particular feature in the best-fitting (and flat) $\beta$-model atmosphere, but higher resolution and more sensitive X-ray observations are required.

NGC 2484.—The ROSAT HRI data are consistent with an unresolved source of luminosity $(3.7 \pm 0.4) \times 10^{42}$ erg s$^{-1}$ (Canosa et al. 1999). The best-fit luminosity in unresolved emission from the PSPC is $3.6 \times 10^{42}$ erg s$^{-1}$, in excellent agreement. Our forthcoming Chandra observation should discriminate between an AGN or compact-gas origin for the unresolved emission. The PSPC radial profile is relatively insensitive to the value of $\beta$ for the extended emission, but prefers a steeper distribution than $\beta = 2/3$, which was assumed by Worrall & Birkinshaw (1994). The radio structure is shown in de Ruiter et al. (1986) to be that of a weak, one-sided jet within a diffuse, low surface-brightness envelope. The minimum pressure in different parts of the radio source is compared with the gas pressure based on the X-ray model in Figure 9.

1040 + 31.—In Canosa et al. (1999), our spatial decomposition of the PSPC data uses a smaller on-source region to probe the unresolved X-ray component. There are no ROSAT HRI observations of this source. Parma et al. (1986) give a map of this source that shows it to have a strong core, a small one-sided jet, fainter lobes, and several “warm spots.” The minimum pressure in the extended emission, estimated by Parma et al. based on their map, is (scaled to our cosmology) about $2 \times 10^{-13}$ N m$^{-2}$, or about double the central pressure in the X-ray–emitting gas. The radio source has a total angular size of about $40^\circ$, roughly equal to the core radius of the X-ray emission.

1855 + 37.—In Canosa et al. (1999), our spatial decomposition of the PSPC data uses a smaller on-source region to probe the unresolved X-ray component, a particularly small fraction of the overall emission. There are no ROSAT HRI obser-
The radio structure has been described by Parma et al. (1986). It appears as a small (10") double source, with a weak additional component to the south. The minimum pressure in the source is approximately $3 \times 10^{-12}$ N m$^{-2}$, comparable to the central pressure implied by the X-ray model, but no information is available on structures less than about 4 kpc in size, which may have higher pressures. Thus, it appears that, like 4C 35.03, the extended structure of this source is limited by external gas pressure, but any jets that may be present on smaller scales are likely to be overpressured.

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