Particles and Fields in Radio Galaxies
ASP Conference Series, Vol. 250, 2001
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New radio-galaxy X-ray results from *Chandra*

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Abstract. The superior spatial resolution of the *Chandra* X-ray Observatory is sharpening our X-ray vision of extragalactic radio sources. Our recent Guest Observer observations of a small sample of B2 radio galaxies show jet X-ray emission to be common in low-power radio galaxies, whereas previously such jets were only X-ray detected in nearby Cen A and M 87. At high redshift, *Chandra* clearly separates AGN-related emission from the surrounding X-ray emitting cluster medium, as illustrated by our results for 3C 220.1 at a redshift of 0.6.

1. Introduction

The *Chandra* X-ray Observatory was launched on July 23rd 1999, and its high sensitivity and spatial resolution (Weisskopf et al. 2000) are already providing dramatic new insights into the small-scale X-ray components associated with radio galaxies. The mildly energy-dependent on-axis point response function (PRF) with the Advanced CCD Imaging Spectrometer (ACIS) instrument has a typical half power diameter of $0.8''$ and FWHM of $0.58''$. This arcsec-level angular resolution corresponds to a spatial resolution in a typical low-power radio galaxy at $z = 0.035$ of ≈ 1 kpc, and a high-power radio galaxy at $z = 0.6$ of ≈ 9 kpc (for $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$).

Before the launch of *Chandra*, ROSAT observations showed that radio galaxies are complex X-ray emitters, and there are examples where the emission arises from hot gas held in the potential well of the group/cluster, inverse Compton or synchrotron processes in radio lobes, hotspots and jets, and from the active-galaxy cores (see Worrall 1999 for a review). In a few cases, notably Cygnus A, there is a component of heavily absorbed X-ray emission from the core, thought to originate close to the AGN. However, most sources have soft compact X-ray emission. The radio to soft X-ray two-point spectral index, $\alpha_{\rm rx}$, is ≈ 0.85 for cores both of low-power radio galaxies and high-power sources where the contribution of inner AGN-related X-ray emission is thought to be negligible, either because the nuclear emission is obscured or because the X-ray core is dominated by beamed emission. A value of $\alpha_{\rm rx} \approx 0.85$ is also measured in resolved knots in the jets of nearby radio galaxies Cen A and M 87, and this has led us to suggest that radio-related X-ray emission with this $\alpha_{\rm rx}$ is generally present at parsec to perhaps kiloparsec distances from the cores (Worrall 1997). However, with ROSAT it is only in the nearest and brightest sources that it is possible to say with confidence that small-scale non-thermal emission has been

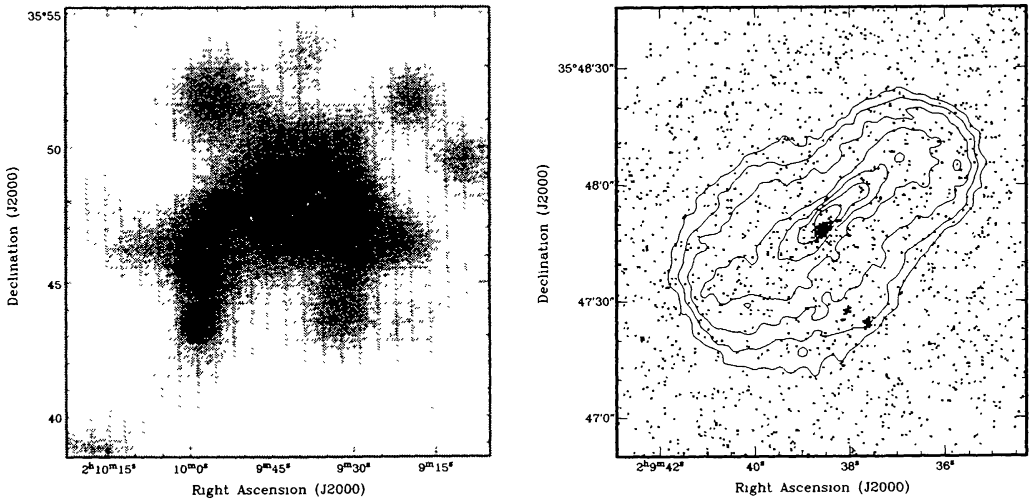

Figure 1. 1.4 GHz contours of B2 0206+35 overlaid on images from ROSAT PSPC (left), preferentially detecting cluster gas, and *Chandra* (right).

detected, since ROSAT's spatial resolution and sensitivity were insufficient to distinguish between truly small-scale nonthermal emission and small-scale hot gas, possibly associated with cooling flows. Furthermore, most ROSAT observations were made with the HRI and yielded no spectral information.

2. Low-Power Radio Galaxies from the B2 sample

Our first observations with *Chandra* of low-power radio galaxies have been short (~ 7 ks) ACIS exposures of B2 0206+35, 0331+39, and 0755+37 (Worrall et al. 2001a). In B2 0206+35 (Figs 1 & 2) and 0755+37 we see three X-ray components within the scale of the optical galaxy: (i) emission associated with the prominent radio jets of 2″ and 4″ length, respectively, (ii) an unresolved component coincident with the radio nucleus, and (iii) emission from galaxy-scale gas of central pressure similar to the minimum pressure in these radio jets, and which may therefore play a role in the jet dynamics. In B2 0331+39 there is no obvious radio jet, either because of small viewing angle, which could superimpose the jet X-ray emission on the core, or because well-collimated kpc-scale plasma is simply absent in this source. The X-ray emission is unresolved. Table 1 lists $\alpha_{\rm rx}$ for the cores and jets; the similarities are notable.

X-ray emission from the cores is not heavily absorbed (as in the case of NGC 6251; see Werner et al. these proceedings), and most plausibly arises from sub-kpc-scale radio structures, a smaller-scale version of the kpc-scale jet-related emission seen in two of the sources. To differentiate between the contending emission mechanisms of synchrotron radiation or inverse Compton scattering requires the deeper observations and larger samples of our ongoing work. We are currently analysing data for four other low-power radio galaxies observed more recently with *Chandra*, two of which are from the B2 sample, and all four

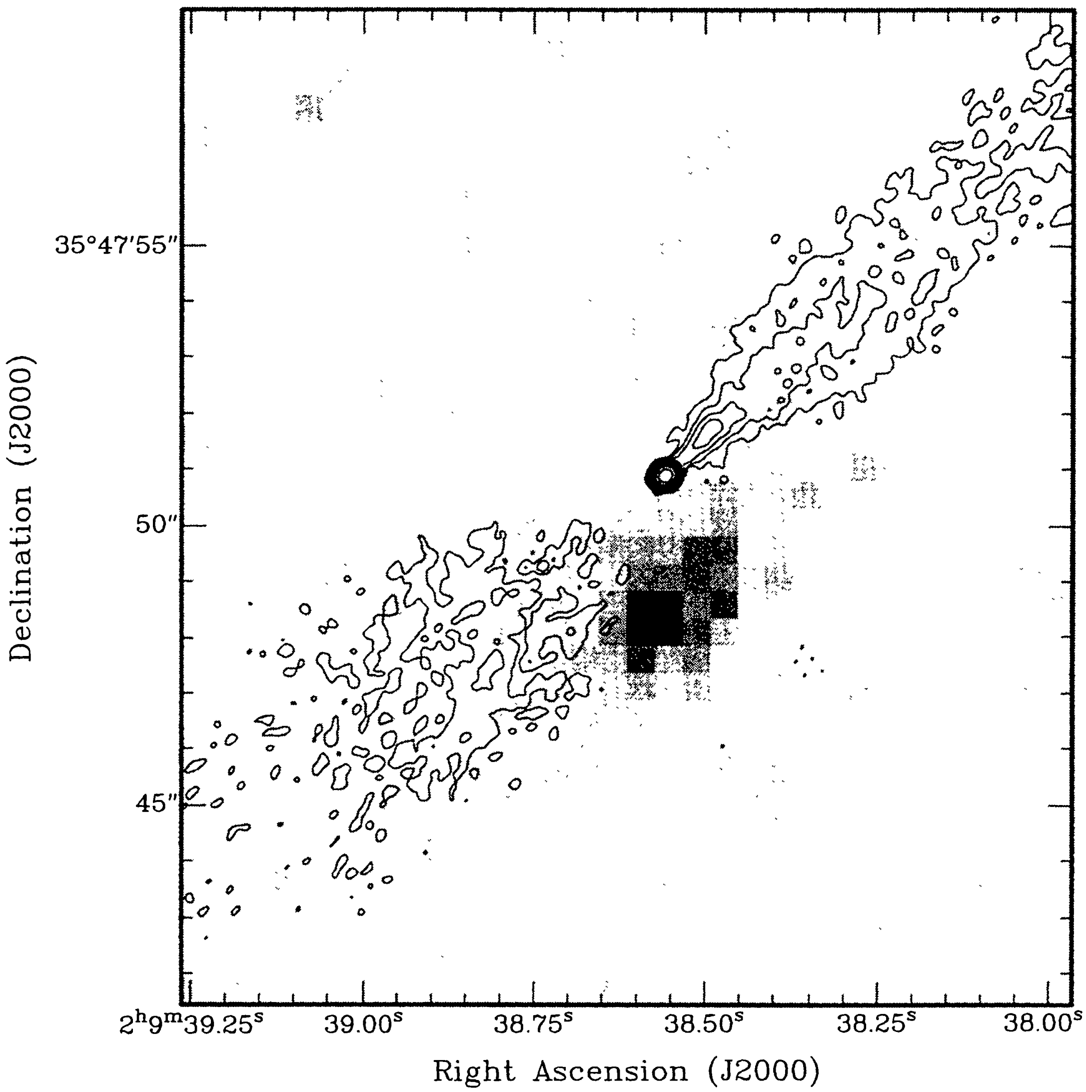

Figure 2. A magnified view of B2 0206+35 with 8.4 GHz contours overlaid on a *Chandra* image shows X-ray extension along the radio jet; the offset between the cores is a known problem with the astrometry applied to these *Chandra* data, uncorrected here for clarity. The *Chandra* data fit emission from core + jet and galaxy-scale gas (Worrall et al. 2001a).

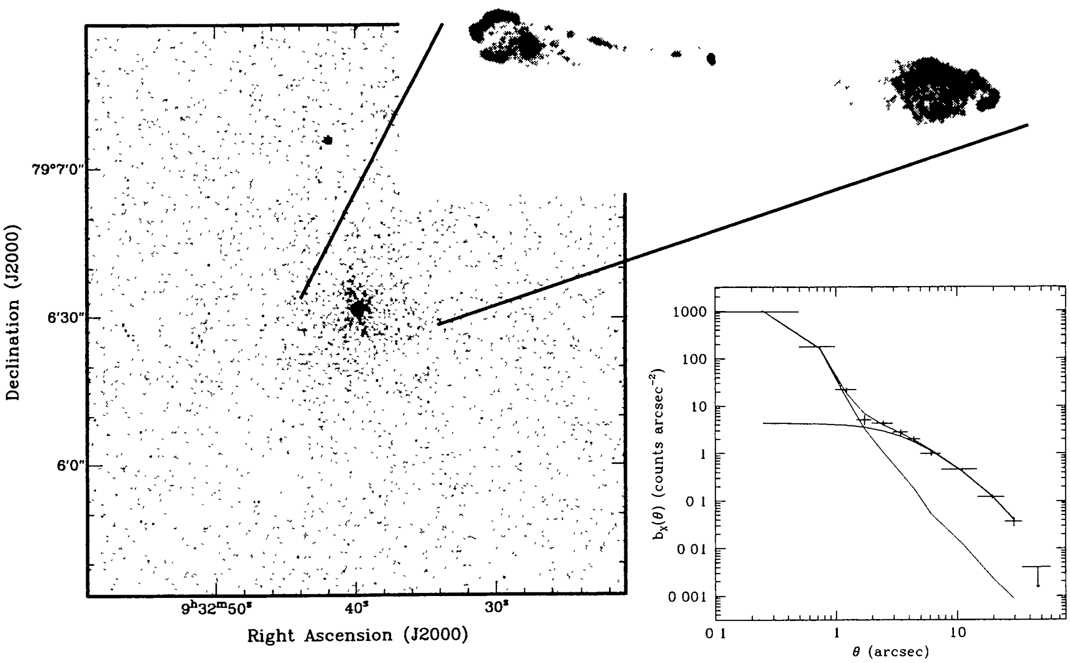

Figure 3. Main picture on left is the *Chandra* image centered on 3C 220.1. An unrelated X-ray point source lies to the north. The insert shows an 8.4 GHz VLA radio image. On the right is the background-subtracted radial profile of the X-ray data for 3C 220.1 with the best-fit model of point-like emission plus a β-model (β = 0.5, core radius = 3.55 arcsec). The contribution of the model to the background region, taken into account in the fitting, is shown dotted. (From Worrall et al. 2001b)

show jet features. At the spatial resolution possible with *Chandra*, X-ray jets are indeed common.

3. High-power Radio Galaxy 3C 220.1

Our first *Chandra* observation of a high-power radio galaxy is an 18 ks exposure with ACIS of the $z = 0.62$ radio galaxy 3C 220.1 (Worrall et al. 2001b). Our modeling of the ROSAT HRI data for the source as a composite of point-like and extended emission (Hardcastle et al. 1998) is strikingly confirmed by the new data (Fig. 3).

The cluster gas supplies pressure in excess of that needed to confine the eastern jet and western lobe, assuming minimum internal energy (see Hardcastle & Worrall, this volume, for inferred consequences). The cluster should be in a giant cooling flow, since the cooling time is shorter than the Hubble time out to a radius of about 15″, but the core X-ray emission is too spiked towards the center for a straightforward model including a large cooling flow. Indeed, the central data fit the PRF well. If we associate the central X-ray emission within the PRF with the radio core, its $\alpha_{\rm rx}$ (Table 1) is less than for other sources, suggesting perhaps that regions close to the AGN dominate the central X-ray output, as is believed to be the case for lobe-dominated quasars.

Table 1. $\alpha_{\rm rx} = \log(l_{5\,\rm GHz}/l_{2\,\rm keV})/7.98$ for Radio-galaxy Cores & Jets

Source	z	type	core $\alpha_{\rm rx}$	jet $\alpha_{\rm rx}$
B2 0206+35	0.0369	FR I	0.91	0.88
B2 0331+39	0.0204	FR I	0.83	–
B2 0755+37	0.0428	FR I	0.85	0.88
3C 220.1	0.62	FR II	0.75	–

Acknowledgments. We thank Raffaella Morganti and Guy Pooley for providing 1.4 GHz data on B2 0206+35 and 8.4 GHz data on 3C 220.1, respectively, and John Biretta for use of his 8.4 GHz archival data on B2 0206+35. We thank staff of the *Chandra* X-ray Center for help with calibrations and software.

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