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EXTENDED AND COMPACT X-RAY EMISSION IN POWERFUL RADIO GALAXIES

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ABSTRACT

We report *ROSAT* X-ray observations of two powerful radio galaxies. 3C 280 provides evidence for a mixture of unresolved and extended emission, with the latter produced by hot plasma of insufficient pressure to confine the radio lobes and insufficient density for a cooling flow to have begun. 3C 220.3 gives only an X-ray upper limit, but one consistent with our interpretation of the X-ray emission from powerful radio-loud AGNs in terms of obscured and unobscured components.

Subject headings: galaxies: active — galaxies: individual (3C 220.3, 3C 280) — radio continuum: galaxies — X-rays: galaxies

1. INTRODUCTION

A major question in the study of powerful radio sources is the extent to which they constitute a single population, with their range of observed properties primarily due to orientation effects caused by anisotropic emission and obscuration. Highly anisotropic emission at many frequencies is an inevitable consequence of the well-established presence of relativistic, self-absorbed, synchrotron plasma, and "unified" schemes explain the essential differences between core-dominated and lobe-dominated quasars by a combination of relativistic beaming and orientation. Such schemes also incorporate the unification of quasars with galaxies of comparable isotropic radio power (Readhead et al. 1978; Readhead 1980), in which anisotropic obscuration hides the broad emission-line regions (Antonucci 1982; Scheuer 1987; Barthel 1989). The current work explores the relationship between radio galaxies and quasars via comparisons of their X-ray and radio properties.

X-ray observations of *quasars* support relativistic beaming through measurement of flux densities which are lower than the predicted self-Compton emission of radio-emitting regions at rest (e.g., Marscher et al. 1979). Correlations of the X-ray emission with properties such as radio core strength, total isotropic radio power, optical emission, and mixtures thereof, have been claimed (Feigelson, Isobe, & Kembhavi 1984; Browne & Murphy 1987; Worrall et al. 1987).

X-ray data for *radio galaxies* of comparably high isotropic radio power to quasars are sparse. The powerful nearby galaxy Cygnus A is dominated by X-ray emission from the cluster in which the galaxy lies (Arnaud et al. 1984). Crawford & Fabian (1993) were the first to report an X-ray detection of a powerful radio galaxy at high redshift, 3C 356. The emission is extended and, by analogy with Cygnus A, they interpret it as due to cluster gas in a cooling flow. Separation of X-ray emission components has been difficult in the past even for nearby low-power radio galaxies (although *ROSAT* is now revealing that both unresolved and extended [thermal] components are typical [Worrall & Birkinshaw 1994]) and remains difficult for high-redshift galaxies.

Here we report *ROSAT* X-ray observations of the powerful high-redshift radio galaxies 3C 220.3 and 3C 280. 3C 280 is detected and provides evidence for a mixture of unresolved and extended X-ray emission. The ratio of X-ray to radio flux densities in the unresolved core component of 3C 280 is comparable to that in core-dominated *quasars* of similar redshift and extended radio power, suggesting that the unresolved X-ray component is synchrotron or self-Compton emission from a jet which is not highly obscured.

2. X-RAY DATA

We observed 3C 220.3 and 3C 280 in soft X-rays with the *ROSAT* Position-Sensitive Proportional Counter (PSPC; Trümper 1983; Pfeffermann et al. 1987) during the pointed phase of the mission (Table 1). SASS versions 5-3 (3C 220.3) and 5-4 (3C 280) were applied to the data to correct for instrumental effects and aspect. We performed additional analysis using the Post Reduction Off-line Software (PROS; Worrall et al. 1992). Conversion between observed count distribution and source flux uses the latest versions of the PSPC response matrix (No. 36) and effective area (No. 2-6). The PSPC point response function (PRF) has been modeled using analytical expressions for the on-axis scattering, focus, and intrinsic detector resolution contributions as a function of energy, applicable to the energy band 0.2–1.9 keV (spectral channels 6–29; Hasinger et al. 1992).

3C 220.3 was undetected; using a background annulus of radii 2′–5′ (excluding a nearby X-ray source), the 3 σ upper limit for the emission (0.17–2.4 keV) is 0.0037 counts s^{-1}. The conversion to flux density is spectrally dependent. If we assume the only absorption is in our Galaxy (Table 1), the 1 keV flux-density limit lies between $\sim$5 and 12 nJy for a power-law spectral energy index α, ($S_\nu \propto \nu^{-\alpha}$), of 2.0–0.5. Later in this paper (see Fig. 3 below) we have adopted a 3 σ upper limit of 11 nJy, appropriate for $\alpha = 1.0$.

We filtered the 3C 280 PSPC data to remove times of high background which occurred on either side of some Earth occultations, leaving an exposure of 46,619 s. 3C 280 was detected with a significance of $\sim$6 σ. Inside a circle of radius 35″, with background from an annulus of radii 3′–4.′3 (excluding two regions contaminated by other sources), 3C 280 gives 71 $\pm$ 12 net counts (0.2–1.9 keV). The X-ray power, which

TABLE 1

OBSERVATIONS

Object	z	log N_H[a]	ROR[b]	Date	Exposure Time (s)
3C 220.3	0.685	20.515	700072	1991 Feb 27	8791
3C 280	0.998	20.086	700073	1991 Jun 2–3	48051

[a] Galactic values from Stark et al. 1992.

[b] *ROSAT* Observation Request number.

is weakly dependent on spectral shape, is $\sim 1.0 \times 10^{36}$ W sr^{-1}. (Friedmann cosmology with $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$, is used throughout.)

The spectrum of 3C 280 is poorly determined. For absorption comparable to that in the line of sight in our Galaxy, the spectrum agrees with a power law, with $0.5 < \alpha < 2.0$ and a 1 keV flux density of 1.7 ± 0.9 nJy. Intrinsic absorption and a steeper power-law slope cannot be excluded, although there are sufficient counts in the low-energy channels to suggest that such absorption is $\lesssim 4 \times 10^{21}$ atoms cm^{-2}. A Raymond & Smith (1977) thermal model also agrees with the data. For Galactic absorption, any temperature $\gtrsim 0.4$ keV is acceptable.

3. X-RAY SPATIAL EXTENT OF 3C 280

A maximum-likelihood centroid for the emission from 3C 280 was found using the PROS, and a background-subtracted radial profile with nine radial bins was extracted for energy range 0.2–1.9 keV (Fig. 1). The background region is described above, and the contribution of the source model in the background annulus (significant for extended models) was taken into account in our model fitting.

A point source alone gives a poor fit to the radial profile. The PRF, modeled assuming an energy weighting which reflects the apparent energies of the detected photons, gives a χ^2 of 60 when compared with the radial profile.

A β model (Cavaliere & Fusco-Femiano 1978; Sarazin 1986) with a core radius of $18''(+13'', -10'')$ and central brightness of 0.068 counts arcsec^{-2} gives a good fit. We have assumed $\beta = \frac{2}{3}$. The fit is formally rather too good ($\chi^2 = 2.5$ for 8 d.o.f.), suggesting that the uncertainties in the background have been overestimated, but the fit is improved still further if the source is modeled with a combination of a point source and β model. The amount of improvement is such that the F-test gives a 5% probability of such a large decrease in χ^2 by chance. The core radius is now $65''(+165'', -45'')$, the central brightness is 0.0074 counts arcsec^{-2}, and the unresolved component contains 60% of the net counts in the region for which the flux density was determined. The improvement of the fit with two components is insensitive to details of the binning.

A contour map of the X-ray emission from 3C 280 (Fig. 2) shows a possible slight asymmetry. The peak of the map is 6″ to the east of the maximum-likelihood centroid: a radial profile extracted with this new center is less smooth but gives qualitatively the same results as Figure 1. The radio lobes of 3C 280 extend only $\sim 18''$, roughly along an EW line (McCarthy, van Breugel, & Kapahi 1991; Liu, Pooley, & Riley 1992) and lie well within the X-ray extent. It is interesting that Gunn et al. (1981) have imaged optically two sources of comparable brightness separated by $\sim 6''$ and which lie roughly along a NE-SW line. The NE object has many narrow and slightly broadened emission lines (Lawrence et al. 1994) and provides the redshift for 3C 280. The SW object has not yet been observed spectroscopically, and it would be of great interest to determine if this is at the same redshift, since this would support a cluster hypothesis, and hence the existence of cluster gas, perhaps explaining the slight asymmetry in the X-ray emission.

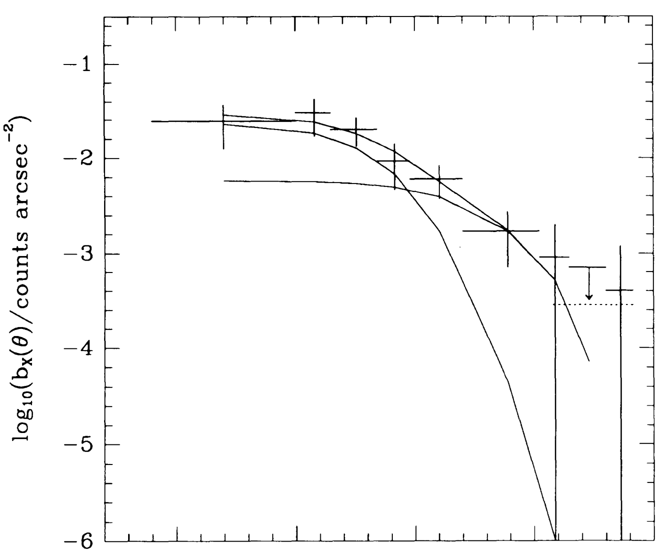

FIG. 1.—Background-subtracted radial profile for 3C 280. The best-fit model (*upper curve*), shown convolved with the PRF and background subtracted for comparison with the data, is a combination of unresolved component (*narrow curve*) and a β model of core radius 65″ (*broad curve*). The *dotted line* shows the contribution of the model to the background annulus.

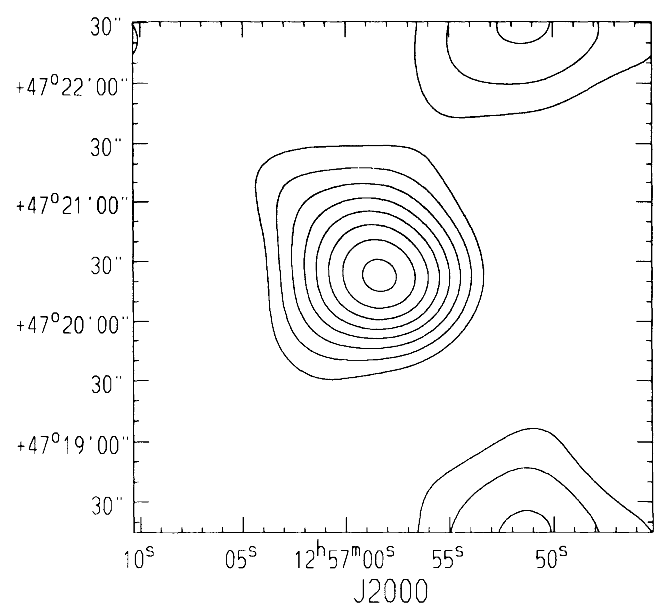

FIG. 2.—X-ray contour plot of 3C 280. The image has been smoothed with a Gaussian of $\sigma = 25''$, a beam size matching the circle of greatest detection significance. Contours are of significance 2–5.5 σ inclusive, in intervals of 0.5 σ. The edges of sources which have been excluded from the background region show up to the NW and SW. The axes show J2000 equatorial coordinates; an error in absolute position of up to $\sim 10''$ is possible due to a problem in *ROSAT*'s aspect determination (Max Planck Institut für Extratterrestriche Physik 1992).

4. DISCUSSION

We have found evidence for both unresolved and extended (and hence presumably thermal) X-ray emission in 3C 280. The evidence for unresolved emission is suggestive, rather than compelling; moreover, the X-ray data do not distinguish between a thermal or a nonthermal origin for the possible unresolved component. However, the evidence for nonthermal X-rays from the nuclei of low-redshift radio galaxies (Fabbiano et al. 1984; Readhead et al. 1983; Worrall & Birkinshaw 1994) and from quasars (e.g., Worrall et al. 1987) leads us to consider seriously the possibility that 3C 280 also emits nonthermal X-radiation from its nucleus. The alternative possibility, that all the X-rays are thermal, has been considered by Crawford & Fabian (1993) for 3C 356. We proceed on the assumption that the unresolved component in 3C 280 is real and from the nucleus.

Figure 3 compares the X-ray and radio-core flux densities of 3C 220.3 and 3C 280 with those of a carefully selected sample of quasars chosen to have low-frequency (isotropic) radio luminosities within a factor of ~20 of the radio galaxies. The quasar sample comprises all the quasars in the complete Pearson-Readhead, Hough-Readhead, and Caltech-Jodrell samples (Pearson & Readhead 1988; Hough & Readhead 1989; Wilkinson et al. 1993) with $z > 0.3$, and which were targets of the *Einstein Observatory* IPC (but not necessarily detected; Wilkes et al. 1994). The fraction, R, of 5 GHz flux density in the core component has a bimodal distribution, in which core-dominated quasars with $R > 0.5$ can be clearly distinguished from lobe-dominated quasars. For 3C 280 we plot the X-ray emission in the unresolved component only, found by multiplying the flux density from our spectral fitting (§ 2) with the percentage of counts in the unresolved component from our spatial fitting (errors are combined in quadrature). Although we have only upper limits for the flux densities of the components of interest for 3C 220.3, they are consistent with the interpretation of the emission of 3C 280 given below.

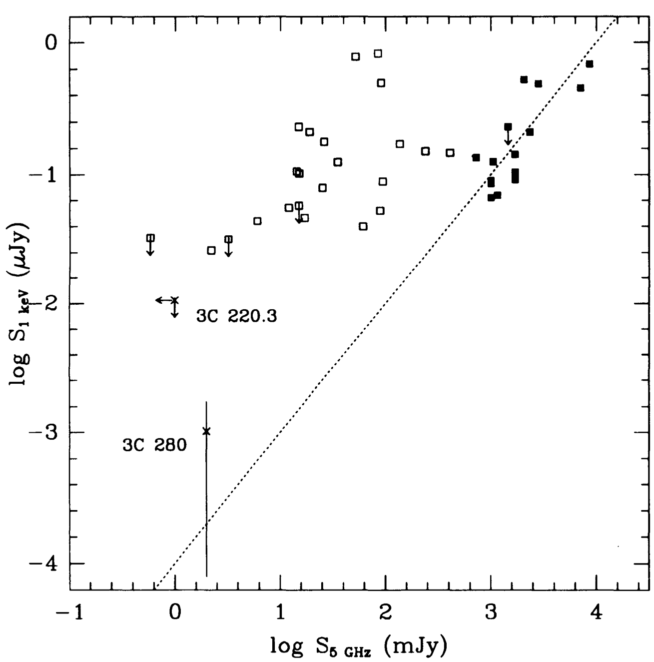

FIG. 3.—Core X-ray and radio flux densities for quasars (*squares*) matched in isotropic radio power with the radio galaxies 3C 220.3 and 3C 280. A line of slope unity (*dotted*) connects 3C 280 with the core-dominated quasars (*filled squares*), but not the lobe-dominated quasars (*open squares*).

In Figure 3 it is clear that for 3C 280 both the compact radio and the unresolved X-ray emission are about three orders of magnitude weaker than in core-dominated quasars of comparable isotropic radio luminosity. (All the sources lie in a relatively narrow band of redshift such that a plot in luminosity density looks similar.) The rough proportionality of X-ray and radio core flux densities between 3C 280 and the core-dominated quasars suggests that these emission components are related, as would be expected were the X-rays due to unobscured synchrotron emission or inverse Compton scattering in the radio emission regions. The radio and X-ray flux densities of the core-dominated quasars themselves are highly correlated (the Spearman rank correlation coefficient is 0.732, with a probability by chance of 0.0019), and seem to follow the same rough proportionality, adding support to this conclusion. For low-redshift ($z < 0.3$) radio galaxies, X-ray/core-radio correlations have been used previously to argue the importance of nuclear X-ray emission (Fabbiano et al. 1984), and in at least two galaxies, NGC 1275 and NGC 6251, evidence for such X-ray emission being of inverse Compton origin has been presented (Readhead et al. 1983; Birkinshaw & Worrall 1993). Here, by analogy, we suggest that the unresolved X-ray emission of a *powerful*, *high-redshift* radio galaxy may be related to its radio core.

The departure of the lobe-dominated quasars from X-ray/radio proportionality (Fig. 3) is evidence for an additional X-ray emission component. Core-dominated sources are believed to have bright cores because their jet emission, enhanced by relativistic boosting toward the observer, swamps all other emission components. However, the X-ray emission from radio-quiet quasars (usually interpreted as unboosted compact emission from the vicinity of the inner part of an accretion disk) is ~50% as luminous as in lobe-dominated quasars (e.g., Worrall et al. 1987). This implies that a significant fraction of the X-ray emission in lobe-dominated quasars may be compact and unboosted rather than jet-related. Figure 3 indicates that the compact emission is obscured (or perhaps absent) in powerful radio galaxies. A fuller discussion of this point will appear elsewhere.

The extended X-ray emission of 3C 280 has been modeled as a thermal gas. Table 2 uses the X-ray parameters of § 3 and equations (10), (11), (13), and (25) of Birkinshaw & Worrall (1993) to derive the central density, the pressure at 10″ from the core (assuming the source is in the plane of the sky), and the cooling time for gas within a core radius of the center. Only if all the X-rays are from gas of low temperature ($\lesssim 1$ keV, whereas $kT \sim 2$–5 keV is expected from the X-ray luminosity and temperature correlation for clusters; David et al. 1993) can a cooling flow have begun, and in the preferred two-component fit to the X-rays, the gas cooling time is greater than the Hubble time for all likely gas temperatures. However, only part of the unresolved X-ray emission need be thermal gas for a cooling flow in the inner regions to be accommodated.

Liu et al. (1992) have calculated the minimum-energy magnetic fields in the radio lobes of 3C 280 to be 4.5 and 6 nT, assuming a filling factor of unity and cylindrical symmetry. Using equation (1) of Miley (1980), this implies a minimum energy density, $u_{\rm min}$, in the stronger lobe $\sim 3 \times 10^{-11}$ J m^{-3}. The corresponding minimum internal pressure of relativistic material, $\frac{1}{3}u_{\rm min}$, is $\sim 1 \times 10^{-11}$ N m^{-2}, higher than the pressure provided by the ambient gas unless all the X-ray emission

TABLE 2

GAS CHARACTERISTICS

Model	kT (keV)	Central Density (cm^{-3})	Pressure 10″ from Core ($N\ m^{-2}$)	t_{cool} within Core Radius (yr)
β only	1	3.2×10^{-3}	8.8×10^{-13}	1.5×10^{10}
	5	3.5×10^{-3}	4.8×10^{-12}	3.0×10^{10}
	9	3.6×10^{-3}	8.8×10^{-12}	3.9×10^{10}
β and unresolved ..	1	5.6×10^{-4}	2.0×10^{-13}	8.4×10^{10}
	5	6.1×10^{-4}	1.1×10^{-12}	1.7×10^{11}
	9	6.2×10^{-4}	2.0×10^{-12}	2.2×10^{11}

in 3C 280 is from thermal gas of high temperature ($\gtrsim$ 9 keV; Table 2). In the preferred two-component fit to the X-rays, the gas pressure is insufficient to confine the lobes, as for some low-redshift radio galaxies (Miller et al. 1985). Overpressure inside the bow shock (e.g., Loken et al. 1992) may be required.

In summary, we find evidence for both unresolved and thermal X-ray emission in the powerful radio galaxy 3C 280. After comparing the unresolved X-ray and core radio emissions with those of radio-loud quasars of similar total (isotropic) power, we find (1) a correlation between the core X-ray and radio emission in core-dominated quasars, (2) 3C 280 lies on an extrapolation of the correlation, and (3) lobe-dominated quasars have X-ray emission in excess of the correlation. The inference from point (1), that the X-rays from core-dominated quasars are beamed, is supported by earlier work. Point (2) is most simply explained if the same core X-ray to radio relationship holds for radio galaxies as for core-dominated quasars; this will be tested by X-ray observations of other powerful radio galaxies. Point 3 suggests that lobe-dominated quasars contain an additional source of X-ray emission, possibly related to the nuclear X-ray emission in radio-quiet quasars. We infer that this compact X-ray component is obscured in radio galaxies, and dominated by beamed emission from the jet in core-dominated quasars.

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