OBSCURATION AND ORIGIN OF NUCLEAR X-RAY EMISSION IN FR I RADIO GALAXIES

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ABSTRACT

We present X-ray observations of the nuclear region of 25 Fanaroff-Riley type I (FR I) radio galaxies from the 3CRR and B2 catalogs, using data from the Chandra and XMM-Newton archives. We find the presence of a X-ray central compact core (CCCX) in 13/25 sources; in 3/25 sources the detection of a CCCX is uncertain, while in the remaining 9/25 sources no CCCX is found. All the sources are embedded in a diffuse soft X-ray component, generally on kiloparsec scales, which is in agreement with the halo of the host galaxy and/or with the intracluster medium. The X-ray spectra of the cores are described by a power law with photon indices \( \Gamma = 1.1 - 2.6 \). In eight sources excess absorption over the Galactic value is detected, with rest-frame column densities \( N_H \sim 10^{20} - 10^{21} \) cm\(^{-2}\); thus, we confirm the previous claim, based on optical data, that most FR I radio galaxies lack a standard optically thick torus. We find significant correlations between the X-ray core luminosity and the radio and optical luminosities, suggesting that at least a fraction of the X-ray emission originates in a jet; however, the origin of the X-rays remains ambiguous. If the X-ray emission is entirely attributed to an isotropic, accretion-related component, we find very small Eddington ratios, \( L_{\text{bol}}/L_{\text{Edd}} \sim 10^{-3} \) to \( 10^{-8} \), and we calculate the radiative efficiency to be \( \eta \sim 10^{-2} \) to \( 10^{-6} \) on the basis of the Bondi accretion rates from the spatial analysis. This suggests that radiatively inefficient accretion flows are present in the cores of low-power radio galaxies.

Subject headings: galaxies: active — galaxies: fundamental parameters — galaxies: nuclei — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

According to unification schemes, radio galaxies are the mis-oriented parent population of jet-dominated blazars and thus correspond to large viewing angles to the jet/torus axes. The low-power (\( P_{178 \text{ MHz}} \leq 2 \times 10^{25} \) ergs s\(^{-1}\)), centrally brightened Fanaroff-Riley type I (FR I) galaxies are the misaligned versions of BL Lac objects, while high-power, edge-brightened FR II galaxies are unified with powerful quasars. Thus, if the unification models for radio-loud sources hold, emission from the cores of both FR I and FR II galaxies should be significantly obscured by dust and gas contained by the torus. Moreover, the accretion flow could be different at high and low powers, with FR II galaxies being powered by a standard disk and FR I galaxies by an advection-dominated accretion flow (ADAF; Reynolds et al. 1996; Ghisellini & Celotti 2001). These questions bear significance to the origin of the FR I/II dichotomy.

While observations from optical to X-rays of FR II galaxies support the presence of an obscuring dusty torus in these sources (Sambruna et al. 1999; Chiaberge et al. 2000), its presence in FR I galaxies is still highly controversial. Optical Hubble Space Telescope (HST) images of FR I galaxies show that in most of these galaxies an unresolved nuclear point source is present (Chiaberge et al. 1999, hereafter CH99; Capetti et al. 2002, hereafter CA02), arguing for a lack of obscuration along the line of sight. The optical flux correlates tightly with the radio core flux, suggesting a nonthermal (synchrotron) origin of the optical emission from the base of the jet (CH99). However, using the same optical and radio data Cao & Rawlings (2004) concluded that in most cases the emission from the central engine of FR I galaxies is heavily obscured and is produced by a standard accretion disk.

At X-rays, FR I galaxies were previously observed with ROSAT and ASCA. The ROSAT observations showed that the cores are embedded in diffuse soft X-ray emission associated with the galaxy’s interstellar medium (ISM). The core X-ray flux correlates with the radio flux, suggesting a jet origin for the X-ray emission (Hardcastle & Worrall 2000). However, a correlation between X-ray and radio fluxes may ensue from a more general correlation (fundamental plane in three-dimensional space) between black hole mass, X-ray emission, and radio emission, where the radio is produced by the jet whereas the X-rays are related to the accretion flow (Merloni et al. 2003). At energies above 2 keV, the ASCA spectra of seven FR I galaxies are best described by a power-law component with photon index \( \Gamma \sim 1.3 - 1.9 \) (Sambruna et al. 1999). Because of the large point-spread function (PSF) of the ASCA detectors, however, contributions from off-nuclear X-ray point sources cannot be excluded (e.g., Turner et al. 1997).

The combination of XMM-Newton and Chandra, with their complementary capabilities, is ideal to study these complex X-ray sources and address, in particular, the issue of nuclear obscuration. The unprecedented spatial resolution of Chandra allows one to disentangle the different components (unresolved core, kiloparsec jet, pointlike sources, diffuse emission) contributing to the X-ray emission. Moreover, with Chandra one
can investigate directly the circumnuclear region, measuring the density and temperature profiles close to the accretion radius of the central black hole. On the other hand, the larger effective area of XMM-Newton and the combination of the EPIC cameras working simultaneously results in a superior photon yield, which allows a more detailed analysis of the nuclear X-ray spectrum. A further advantage of XMM-Newton is that bright pointlike sources are not affected by pileup problems, which is unfortunately common in Chandra observations. In fact, the advantage of the complementary use of XMM-Newton and Chandra was demonstrated in a previous study of the FR I galaxy 3C 270 (Gliozzi et al. 2003).

Here we extend this study to archival FR I galaxies in order to test the unification models and the origin of the FR I/II division. The basic questions we address are: (1) Do FR I galaxies have obscuring tori? Does the column density correlate with luminosity and/or inclination angle? (2) What is the origin of the nuclear X-ray emission? How much does the beamed component contribute to the nuclear X-ray flux? (3) If the X-rays originate from the accretion flow, what is the nature of accretion in the nuclei of FR I galaxies?

The outline of the paper is as follows. In §2 we discuss the sample selection criteria and in §3 we discuss the observations and data analysis. Results of the spatial and spectral analysis are given in §4. Correlations between parameters are presented in §5, while the interpretation of the results is given in §6. Throughout this paper, $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ are adopted.

2. SAMPLE AND X-RAY OBSERVATIONS

We started with the samples presented in CH99 and CA02. The CH99 sample contains 33 radio galaxies belonging to the 3CR catalog (Spinrad et al. 1985) and morphologically identified as FR I radio sources by Laing et al. (1983) and/or Zirbel & Baum (1995). The CA02 sample, on the other hand, contains 57 radio galaxies belonging to the B2 catalog (Colla et al. 1975; Fantin et al. 1978). These samples contain all the bona fide FR I radio galaxies observed in the optical with HST.

We cross-correlated the CH99 and CA02 samples with the Chandra and XMM-Newton archives and selected all the sources with available X-ray observations up to 2004 January. The final sample, which contains 25 sources, is reported in Table 1. Also listed are redshifts and radio, optical, and UV luminosities from CH99 and CA02. The inclination angles of the radio jet with respect to the line of sight listed in column (5) were obtained from the literature, specifically from the sources listed in column (6). The inclination angles are usually determined from high-resolution radio data using the brightness ratio between the parsec-scale jet and the counterjet, and/or the arcsecond-scale core dominance with respect to the total power...
of the source (e.g., Giovannini et al. 2001). Unfortunately, for many sources no uncertainties are reported in the literature. Column (7) lists the mass of the central black hole, derived from the correlation between the stellar velocity dispersion of the host bulge and its B-band magnitude (Marchesini et al. 2004). Among the 25 sources available in the Chandra and XMM-Newton archives, 11 have only Chandra observations (1 source with ACIS-I and 10 with ACIS-S), three have only XMM-Newton observations, and the remaining 11 have been observed with both satellites. For the sources with both Chandra and XMM-Newton observations, the former satellite has been used for the spatial analysis (except for 3C 84, which is affected by severe pileup). Also, for the spectral analysis Chandra observations have been preferred because of the ability to disentangle the nuclear from the diffuse component; however, in four cases (B2 0120+33, B2 0149+35, 3C 274.0, and 3C 338) XMM-Newton observations have been used owing to the poor Chandra spectra. The log of the X-ray observations is reported in Table 2.

3. X-RAY OBSERVATIONS AND DATA REDUCTION

3.1. Chandra

The Chandra observations were carried out between 2000 April and 2004 January. All were performed with ACIS-S, with the sources at the nominal aimpoint of the S3 chip, except for 3C 28, which was observed with ACIS-I. In several cases, the original observers requested a reduced frame time to mitigate core pileup. In the case of 3C 78, no reduced time frame was requested because of significant pileup (28%). No spatial or spectral analysis was performed for this object. The ACIS event files were screened using CIAO version 2.3 according to standard criteria.

Background spectra and light curves were extracted from source-free regions on the same chip as the source. Time intervals corresponding to background flares were excluded. The net exposure times are listed in Table 2. Spectra were extracted from a circular region with radius 15" (see § 4.1), and their response matrices were constructed using the corresponding thread in CIAO version 2.3. The ACIS spectra were analyzed in the energy range 0.3–8 keV, in which the calibration is known and the background negligible.

3.2. XMM-Newton

Given that the cores of FR I galaxies are relatively weak X-ray emitters, we used only data from the EPIC pn and MOS cameras for our analysis. These were performed using different observing modes (extended and full frame) and different filters (thin and medium), as specified by the original observers.
No core pileup was detected in either the pn or MOS cameras according to the SAS task `epatplot`. The recorded events were screened to remove known hot pixels and other data flagged as bad. For *XMM-Newton*, only data with FLAG = 0 were used. The data were processed using the latest CCD gain values, and only events corresponding to pattern 0–12 (singles, doubles, triples, and quadruples) in the MOS cameras and 0–4 (singles and doubles only, since the pn pixels are larger) in the pn camera were accepted. *Arf* and *rmf* files were created with the *XMM-Newton* Science Analysis Software (SAS) version 5.4.

EPIC spectra were extracted in circular regions centered on the core and with radii 20″–30″, depending on the intensity and the location on the chip of the source. Spectral analysis was performed in the energy range 0.2–10 keV.

4. RESULTS

4.1. Spatial Analysis

Figures 1 and 2 show the *Chandra* and *XMM-Newton* images of the sources, with the soft X-ray contours in 0.3–2 keV overlaid on the hard X-ray (2–8 keV) images. Both soft and hard X-ray images were smoothed using the subpackage `fadapt` of FTOOLS with a circular top hat filter of adaptive size in order to achieve a minimal number of 10 counts under the filter. Inspection of Figures 1 and 2 shows the presence of diffuse soft X-ray emission in all sources. In most cases, the diffuse emission is on kiloparsec scales and is associated with the host galaxy halo. In 3C 28, B2 0120+33, B2 0149+35, 3C 84, 3C 272.1, B2 1346+26, 3C 317, and 3C 338 the soft X-rays appear to extend on larger, cluster-like scales. Hard X-ray point sources are present in several cases (see below). X-ray jets are present in B2 0055+30 (Worrall et al. 2003), 3C 31 (Hardcastle et al. 2002), 3C 66B (Hardcastle et al. 2001), B2 0755+37 (Worrall et al. 2001), 3C 270 (Chiaberge et al. 2003b), and 3C 274.0 (Marshall et al. 2002; Wilson & Yang 2002).

Since this paper focuses on the X-ray emission from the radio galaxy cores, it is important to know in how many cases an unresolved X-ray source is detected. To quantify this, we performed a detailed spatial analysis of the *Chandra* and *XMM-Newton* data.

We adopted the following procedure. First, radial surface brightness profiles were extracted from a series of concentric annuli centered on the radio core position. Off-nucleus X-ray point sources, as well as the X-ray jet, were excluded. Second, the radial profiles were fitted with a model including the instrument PSF and one or more β models to describe the diffuse soft X-ray emission. The significance of the PSF was determined using an *F*-test, assuming as a threshold for significant detection of the PSF a probability *P* ≥ 99%, corresponding to a 3σ confidence level.

For the *XMM-Newton* images, the PSF was described using the analytical description of Ghizzardi (2001). Since the aim point of the EPIC pn camera is very close to the edge of the CCD (limiting the extension of the extraction regions to few arcseconds), we decided to use only the EPIC MOS1 data. For the *Chandra* images, the PSF was created using the *Chandra* Ray Tracer (CharT) simulator, which takes into account the spectral distribution of the source. The ACIS PSF was thus described using the six-parameter function

\[
PSF(\alpha) = A_0 e^{-\alpha_1 x^2} + A_3 e^{-\alpha_4 x^4} + A_5 e^{-\alpha_6 x^6},
\]

where the free parameters were determined by fitting the radial profile of the PSF.

The β-model is described by the formula (e.g., Cavaliere & Fusco-Femiano 1976)

\[
S(r) = S_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-\beta+1/2}.
\]

Table 3 summarizes the X-ray core detections, while Table 4 lists the best-fit parameters (core radius, β-value) for the β-models. Three examples of the fit of radial profiles are shown in Figure 3.

Column (2) of Table 3 flags those FR I galaxies in which a compact central core (CCC) was detected with *HST* in the optical. For analogy, we use the term CCCX to indicate the CCC counterpart in the X-rays. As is apparent from Table 3, a CCCX was detected in 13/25 sources, while no CCCX is present in nine sources. In the case of B2 2116+26, the PSF is significant at *P* = 95.6%, corresponding to a 2σ confidence level. However, the *Chandra* observation is one of the shortest, with only 9.6 ks of live time. We regard this source as a likely CCCX candidate. The remaining three sources—3C 78, 3C 264, and 3C 272.1—are discussed here individually.

3C 78.—Because of the strong core pileup, which distorts the shape of the PSF, no reliable fit to the radial profiles could be performed. However, the presence of central pileup is a per se indication of strong unresolved X-ray emission. Therefore, we conclude that a CCCX is present in 3C 78.

3C 264.—The PSF is dramatically distorted owing to the large offset from nominal aimpoint of the source. Thus, no reliable spatial analysis can be performed. However, the source spectrum (see Table 5) shows the presence of a hard X-ray power-law component. We interpret this component as the signature of nonthermal emission from an active galactic nuclei (AGN). We consider the detection of a CCCX uncertain in this case.

3C 272.1.—The *Chandra* image shows soft X-ray emission with a very disturbed morphology. The radial profile cannot be properly fitted with a β-model(s), since the spatial fit does not converge. Since the inspection of the hard X-ray image shows the presence of a point source, we conservatively consider the CCCX detection uncertain.

Let us now compare the detection rate of the CCCs and CCCXs. We find that:

1. Of the 18 FR I galaxies with a CCC in the optical, 13 also have a CCCX.
2. All FR I galaxies with a detected CCCX have a detected CCC, except 3C 438.
3. No compact core was detected in either optical or X-rays in three FR I galaxies (3C 28, B2 0120+33, and B2 1257+28).

There are two possible explanations for the nondetection of a CCCX: either the AGN X-ray emission is intrinsically weak (below the detection threshold of *Chandra* or below the level of the circumnuclear extended emission), or it is absorbed by a very large amount of cold gas, *N* _H ≥ 10²⁴ cm⁻². The first case is discussed in § 4.3, while the second case is discussed in § 6.1.

4.2. Variability Analysis

We searched for X-ray flux variability in the background-subtracted light curves of the sources with positive CCCX detections. When possible, *XMM-Newton* data were used to take advantage of the larger signal-to-noise ratio of the EPIC data. According to a *χ²* test for constancy, no significant variability of the 2–10 keV flux is detected in the sources of our sample,
except for 3C 270. For more details on this source, we refer to Gliozzi et al. (2003).

4.3. Spectral Analysis

The main goal of the X-ray spectral analysis is to investigate the physical conditions of the sources in the sample, focusing on the nonthermal emission from the 15 detected CCCXs. We also include the two CCCX candidates, 3C 264 and 3C 272.1, while 3C 78 was not considered because of the strong core pileup problems.

The ACIS and EPIC spectra, extracted as described above (§ 3), were grouped so that each new bin had $\geq 20$ counts to
enable the use of the $\chi^2$ statistics. For 3C 438, for which $\lesssim 200$ counts were detected, the X-ray spectrum was not rebinned and the C-statistic was used instead. The spectra were fitted using XSPEC version 11.2.0. Errors quoted throughout are 90% for one interesting parameter ($\Delta \chi^2 = 2.7$).

The X-ray spectra were fitted with a two-component model, both absorbed by Galactic $N_H$. At soft energies, the circumnuclear emission from the host galaxy and/or from the cluster was parameterized by a thermal component, the model $apec$ in XSPEC, with temperature $kT$ and abundance $Z/Z_\odot$. During the fits, the abundance was left free to vary between 0.2 and 1, or otherwise fixed at one of these two limits. For sources embedded in a galaxy cluster, often more than a single thermal component was required to adequately fit the data, since the cluster can have a gradient of temperatures and/or abundances in the ACIS/EPIC extraction radii.

Fig. 2.—Same as Fig. 1, except that the X-ray images for 3C 84, 3C 264, 3C 449, and 3C 465 are from XMM-Newton EPIC MOS1. [See the electronic edition of the Journal for a color version of this figure.]
X-ray count rate of the core in the energy range 2–10 keV from an extraction radius of 1 arcsec. The significance of the PSF, from the upper limit (CH99; CA02). Col. (3): Detection of the X-ray CCC: Y = yes, N = no, U = uncertain. Col. (4): Normalization of the PSF, from the F-test. Col. (5): Satellite name: C = Chandra, X = XMM-Newton. Col. (6): X-ray count rate of the core in the energy range 2–10 keV from an extraction radius of 1 arcsec.

### TABLE 3
RESULTS OF THE X-RAY SPATIAL ANALYSIS

| Source (1) | Optical (2) | X-Ray (3) | Core Significance (%) (4) | Satellite (5) | Count Rate (6) |
|------------|-------------|-----------|---------------------------|---------------|----------------|
| 3C 28      | Up          | N         | 92.9                      | C             | <0.001         |
| B2 0055+30 | Up          | Y         | >99.9                     | C             | 0.035 ± 0.001 |
| 3C 31      | Y           | Y         | >99.9                     | C             | 0.003 ± 0.001 |
| B2 0120+33 | Up          | N         | 12.4                      | C             | <0.001         |
| B2 0149+35 | D           | N         | 38.7                      | C             | <0.001         |
| 3C 66B     | Y           | Y         | >99.9                     | C             | 0.006 ± 0.001 |
| 3C 78      | Y           | U         | ...                       | C             | 0.053 ± 0.003 |
| 3C 84      | Y           | Y         | >99.9                     | X             | 2.815 ± 0.011 |
| B2 0755+37 | Y           | Y         | >99.9                     | C             | 0.009 ± 0.001 |
| 3C 264     | Y           | U         | ...                       | X             | 0.020 ± 0.001 |
| 3C 270     | Y           | Y         | 99.9                      | C             | 0.016 ± 0.001 |
| 3C 272.1   | Y           | U         | ...                       | C             | 0.005 ± 0.001 |
| 3C 274.0   | Y           | Y         | >99.9                     | C             | 0.052 ± 0.002 |
| B2 1256+28 | D           | N         | ...                       | X             | <0.160*       |
| B2 1257+28 | Up          | N         | 30.2                      | C             | <0.001        |
| B2 1346+26 | Y           | N         | 22.3                      | C             | 0.002 ± 0.001 |
| 3C 317     | Y           | Y         | >99.9                     | C             | 0.006 ± 0.001 |
| 3C 338     | Y           | Y         | 99.9                      | C             | 0.002 ± 0.001 |
| 3C 346     | Y           | Y         | >99.9                     | C             | 0.017 ± 0.001 |
| 3C 348     | Y           | N         | 21.4                      | C             | <0.001        |
| B2 2116+26 | Y           | N         | 95.6                      | C             | 0.002 ± 0.001 |
| 3C 438     | Up          | Y         | >99.9                     | C             | <0.001        |
| 3C 449     | Y           | Y         | >99.9                     | X             | 0.012 ± 0.001 |
| B2 2236+35 | Y           | N         | 15.4                      | C             | <0.001        |
| 3C 465     | Y           | Y         | >99.9                     | X             | 0.023 ± 0.002 |

Notes.—Col. (1): Source name. Col. (2): Detection of the optical CCC: Y = yes, D = dusty galaxy, Up = upper limit (CH99; CA02). Col. (3): Detection of the X-ray CCC: Y = yes, N = no, U = uncertain. Col. (4): Normalization of the PSF, from the F-test. Col. (5): Satellite name: C = Chandra, X = XMM-Newton. Col. (6): X-ray count rate of the core in the energy range 2–10 keV from an extraction radius of 1 arcsec.  
* 3 σ upper limit.

### TABLE 4
RESULTS OF FITS OF RADIAL PROFILES

| Source (1) | Core Radius (arcsec) (2) | β (3) | Normalization (10^-4 counts s^{-1} arcsec^{-2}) (4) |
|------------|--------------------------|-------|--------------------------------------------------|
| 3C 28      | 6.24 ± 0.58              | 0.42 ± 0.04 | 3.2 ± 0.1                                      |
| B2 0055+30 | 1.98 ± 0.20              | 0.54 ± 0.03 | 23.8 ± 3.2                                     |
| 3C 31      | 3.46 ± 0.39              | 0.68 ± 0.10 | 7.0 ± 0.8                                      |
| B2 0120+33a| 0.59 ± 0.09              | 0.46 ± 0.04 | 52.3 ± 7.5                                     |
| B2 0149+35 | 11.16 ± 0.54             | 0.42 ± 0.02 | 5.0 ± 0.1                                      |
| 3C 66B     | 0.49 ± 1.02              | 0.49 ± 0.07 | 45.4 ± 17.0                                    |
| 3C 84      | 104.09 ± 0.76            | 0.64 ± 0.01 | 11.6 ± 0.1                                     |
| B2 0755+37 | 0.59 ± 0.59              | 0.60 ± 0.16 | 107.5 ± 107.5                                  |
| 3C 270     | 0.98 ± 0.07              | 0.52 ± 0.01 | 126.7 ± 14.5                                   |
| 3C 274.0   | 0.22 ± 0.20              | 0.24 ± 0.01 | 104.6 ± 43.2                                   |
| B2 1257+28 | 1.48 ± 0.15              | 0.67 ± 0.01 | 16.7 ± 2.9                                     |
| B2 1346+26 | 3.23 ± 0.54              | 0.25 ± 0.01 | 16.1 ± 0.9                                     |
| 3C 317     | 38.61 ± 0.22             | 0.67 ± 0.01 | 5.8 ± 0.1                                      |
| 3C 338     | 12.91 ± 0.36             | 0.34 ± 0.01 | 11.5 ± 0.2                                     |
| 3C 346     | 0.10 ± 0.10              | 0.30 ± 0.06 | 7.3 ± 6.6                                      |
| 3C 348a    | 4.05 ± 0.70              | 0.75 ± 0.30 | 11.5 ± 1.1                                     |
| B2 2116+26 | 1.11 ± 0.28              | 0.48 ± 0.03 | 17.5 ± 6.2                                     |
| 3C 438a    | 13.81 ± 2.89             | 0.87 ± 0.61 | 1.9 ± 0.1                                      |
| 3C 449     | 106.20 ± 24.62           | 0.71 ± 0.14 | <0.1                                            |
| B2 2236+35 | 0.74 ± 0.15              | 0.48 ± 0.04 | 26.7 ± 6.4                                     |
| 3C 465     | 194.50 ± 43.44           | 0.60 ± 0.34 | <0.1                                            |

Notes.—Col. (1): Source name. Col. (2): Core radius. Col. (3): β-parameter. Col. (4): Normalization of the β-model. Uncertain detections (3C 78, 3C 264, and 3C 272.1) are not considered.  
* An additional β-model is necessary.
At hard X-rays, a power-law model with photon index $\Gamma$ was used to describe the CCCX nonthermal emission. The power law is absorbed by a column density $N_H$ at the redshift of the source, thus representing any excess intrinsic absorption over the Galactic value. We note that most CCCXs are at low $z$; thus, absorption by the ISM along the line of sight is likely not to be significant. The significance of the power-law component over the thermal model was determined with the $F$-test.

The results of the spectral fits are presented in Table 5. Three spectra are shown in Figure 4, corresponding to the three qualitatively different surface brightnesses shown in Figure 3. For all the sources with a detected CCC in X-rays, the power-law

![Graphs showing radial profiles for three sources observed with ACIS.](image)

**Fig. 3.**—Examples of radial profiles for three sources observed with ACIS. In the top panels, the dashed line is the instrumental PSF and the dot-dashed line represents the $\beta$-model describing the diffuse emission. The continuous thick line is the total model, while the thin dotted horizontal line is the background. The residuals of the best-fit model are shown in the bottom panels. The PSF is detected with high (>99.9%) significance in 3C 346, moderate (96%) significance in B2 2116+26, while it is not required in the case of B2 0149+35.

### Table 5

**Core X-Ray Spectral Analysis**

| Source      | Satellite | $kT_1$ (keV) | $Z_1$ | $kT_2$ (keV) | $Z_2$ | $N_H$ (10$^{21}$ cm$^{-2}$) | $\Gamma$ | $\chi^2$/dof |
|-------------|-----------|--------------|-------|--------------|-------|----------------|---------|-------------|
| **Confirmed CCCX** | | | | | | | | |
| B2 0055+30  | C         | 0.51±0.05 0.51±0.05 | 1.0   | 0.82±0.17 0.82±0.17 | 0.2   | 72.7±18.4 72.7±18.4 | 1.56±0.17 1.56±0.17 | 0.97/153 |
| 3C 31       | C         | 0.69±0.06 0.69±0.06 | 0.2   | 0.80±0.06 0.80±0.06 | 1.0   | 2.17±0.14 2.17±0.14 | 1.03/33  |
| 3C 66B      | C         | 0.36±0.06 0.36±0.06 | 1.0   | 0.84±0.17 0.84±0.17 | 0.2   | 8.0±1.6  8.0±1.6  | 1.29±0.65 1.29±0.65 |
| 3C 84a      | X         | 2.38±0.06 2.38±0.06 | 1.0   | 0.82±0.04 0.82±0.04 | 0.2   | 8.0±1.6  8.0±1.6  | 1.29±0.65 1.29±0.65 |
| B2 0755+37  | C         | 0.26±0.06 0.26±0.06 | 0.2   | 0.80±0.06 0.80±0.06 | 1.0   | 2.18±0.19 2.18±0.19 | 0.67/15  |
| 3C 270      | C         | 0.60±0.06 0.60±0.06 | 1.0   | 1.16±0.06 1.16±0.06 | 1.0   | 702.6±207.2 702.6±207.2 | 1.09±0.23 1.09±0.23 | 1.04/60  |
| 3C 274.0b   | X         | 0.10±0.06 0.10±0.06 | 0.2   | 1.16±0.06 1.16±0.06 | 1.0   | 2.3±0.5  2.3±0.5  | 1.31/57  |
| 3C 317      | C         | 0.18±0.06 0.18±0.06 | 1.0   | 0.80±0.06 0.80±0.06 | 1.0   | 1.81±0.13 1.81±0.13 | 0.98/52  |
| 3C 338      | X         | 2.23±0.06 2.23±0.06 | 1.0   | 0.31±0.04 0.31±0.04 | 1.0   | 15.4±4.7 15.4±4.7  | 2.15±0.16 2.15±0.16 |
| 3C 346      | C         | 0.64±0.06 0.64±0.06 | 0.2   | 0.80±0.06 0.80±0.06 | 1.0   | 1.69±0.09 1.69±0.09 | 1.06/101 |
| 3C 438      | C         | 0.30±0.06 0.30±0.06 | 0.2   | 1.26±0.06 1.26±0.06 | 1.0   | 15.4±4.7 15.4±4.7  | 2.15±0.16 2.15±0.16 |
| 3C 449      | X         | 0.58±0.06 0.58±0.06 | 0.2   | 1.26±0.06 1.26±0.06 | 1.0   | 14.5±4.7 14.5±4.7  | 2.13±0.16 2.13±0.16 |
| 3C 465      | X         | 0.97±0.06 0.97±0.06 | 1.0   | 1.26±0.06 1.26±0.06 | 1.0   | 25.7±10.9 25.7±10.9 | 2.95±0.17 2.95±0.17 |
| **Candidate CCCX** | | | | | | | | |
| 3C 264      | X         | 0.33±0.06 0.33±0.06 | 0.2   | 0.80±0.06 0.80±0.06 | 1.0   | 17.8±4.9 17.8±4.9  | 2.48±0.04 2.48±0.04 | 0.92/290 |
| 3C 272.1    | C         | 0.61±0.06 0.61±0.06 | 0.8   | 1.26±0.06 1.26±0.06 | 1.0   | 20.6±4.9 20.6±4.9  | 2.06±0.04 2.06±0.04 | 0.61/28  |

Notes.—Col. (1): Source name. Col. (2): Satellite data used for the spectral analysis ($C=Chandra$, $X=XMM-Newton$).Cols. (3) and (5): Temperature. Cols. (4) and (6): Abundance $Z/Z_{\odot}$. Col. (7): Absorption column density at the source’s redshift. Col. (8): Photon index $\Gamma$ of the power-law component. Col. (9): Reduced $\chi^2$ of the fit and degrees of freedom.

* Additional thermal component necessary: $kT_1 = 0.17 \pm 0.02, Z_1 \geq 0.6$.
* Additional thermal component necessary: $kT_2 = 0.81 \pm 0.02, Z_2 \leq 0.5$.
* Values of C-statistics and PHA bins.
component is always required at a high significance level \((P_F \geq 95\%)\). For the sources without a CCCX, the power law is not required and the X-ray spectrum is adequately described by one or multiple thermal components.

In eight sources, statistically significant absorption over the Galactic value is detected, with \(N_H \sim 10^{20} - 10^{21} \text{cm}^{-2}\) (see also Fig. 5). The source 3C 270 stands out by having the largest intrinsic column density, \(N_H \sim 10^{22} \text{cm}^{-2}\), in agreement with previous findings (Gliozzi et al. 2003). The power-law photon index spans a wide range of values, \(\Gamma \sim 1.1-2.6\), with average value \(\langle \Gamma \rangle = 1.9\) and standard deviation \(\sigma = 0.4\).

Most of the FR I galaxies of the our sample are embedded in diffuse emission on the scale of the host galaxy halo, approximately several kiloparsecs (Table 4). The fitted temperatures are \(kT \sim 0.3-1 \text{ keV}\), in agreement with previous results (Sambruna et al. 1999; Worrall & Birkinshaw 2000).

The observed fluxes and intrinsic (absorption-corrected) luminosities in the energy range 0.3–8 keV are reported in Table 6. Also listed in the table are the observed fluxes and intrinsic luminosities in 0.3–8 keV for the power-law component only. The latter span 3 orders of magnitude, with \(L_X \sim 10^{40} - 10^{43} \text{ ergs s}^{-1}\). Comparing the values in Table 6, it is apparent that the AGN power-law emission typically contributes \(\geq 50\%\) of the total X-ray emission. This result is independently confirmed by the analysis of the radial profiles: evaluating the integrated area under the PSF and under the \(\beta\)-model over the inner 20\(^\circ\), we find that the PSF-to-total flux ratio is \(\geq 50\%\).

In the cases of 3C 28, B2 0149+35, and B2 2116+26, no power-law component was required in the X-ray spectrum, in line with the fact that a CCCX is not detected in these sources. However, limits to the contribution of the X-ray emission due to the AGN can be derived from the radial profiles (e.g., Fig. 3). While the PSF is not statistically significant, the normalization on the PSF can be used to calculate an upper limit on the relative AGN contribution to the total X-ray emission. We find that the AGN contributions are on the order of \(~6\%\), \(~1\%\), and \(~30\%) respectively.

For the remaining five sources with undetected CCCXs, we used the most conservative value of the ratio \((\sim 1\%)\) to derive the upper limit on the AGN luminosity. The values are reported in Table 6.

5. CORRELATIONS

We have investigated possible trends among various parameters related to the core emission, namely, the X-ray, optical, and radio luminosities, the absorption column density, and the inclination angle of the radio jet. The goal is to uncover clues as to the origin of the X-ray emission and on the presence of an obscuring torus, as expected in the context of unification models.

To quantify the degree of linear correlation, we calculated the linear correlation coefficient \(|r|\) and computed the chance probability \(P_c(N)\) that a random sample of \(N\) uncorrelated pairs of measurements would yield a linear correlation coefficient equal or larger than \(|r|\). If the chance probability is small, the two quantities are likely to be correlated. We use as a minimum probability of correlation \(P_c(N) < 1\%\) (which corresponds to a 3 \(\sigma\) level). To account for upper limits, we used the generalized Kendall’s Tau test contained in the statistical package ASURV (Lavalley et al. 1992). The chance probabilities and the linear correlation coefficients with the intercept coefficient and slope of the linear regression \((y = a + bx)\) are shown in Table 7 for both the detections only and when limits are included.

Figure 6a shows the plot of the intrinsic column density \(N_H^*\) (Table 6) versus the inclination angle of the jet (Table 1). According to the unification schemes, the obscuring torus becomes more prominent for larger viewing angles, so we would expect a trend of larger \(N_H^*\) for larger angles. No such trend is present in Figure 6a over three decades in \(N_H^*\) and a factor of 4 in angle. We conclude that FR I galaxies lack a standard thick obscuring torus, in contrast to expectations from the unification models.
In Figure 6b, we show the plot of the intrinsic X-ray luminosity of the AGN versus the inclination angle of the radio jet. Formally, a linear regression analysis shows that there is no significant correlation. However, if the outlying sources 3C 338 and 3C 438 are excluded, a marginally significant correlation is detected, $P_r(N) = 2.3\%$. The correlation becomes statistically significant, $P_r(N) = 0.5\%$, if only the Chandra data (without 3C 438) are considered. The trend is of decreasing X-ray luminosity with increasing angle, as expected if a fraction of the X-ray emission is anisotropic, for example, related to a beamed component. Indeed, the X-ray luminosity also correlates tightly with the radio and optical luminosities (Figs. 6c and 6d), for which an origin from the unresolved jet was argued (CH99; Hardcastle & Worrall 2000; CA02).

As for the outliers, we note that 3C 438 is classified as an FR I radio galaxy by CH99 but as an FR II galaxy by Rawlings et al. (1989): it is thus possible that this source is an intermediate FR I/II galaxy. In the case of 3C 338, the nucleus shows a high X-ray to submillimeter luminosity ratio compared with other 3C radio sources (Quillen et al. 2003). Both sources can thus be considered “anomalous” in the present sample.

A label in Figure 6b marks the position of 3C 274.0 (M87) and 3C 270. The first source is interesting because it was argued recently on the basis of the Chandra data that the X-ray core flux originates from the base of the jet (Marshall et al. 2002); however, in Figure 6b this source has a deficit of X-ray emission. Variability could possibly account for this discrepancy.

### TABLE 6
**Sources X-ray Fluxes and Luminosities**

| Source     | Total Flux $(10^{-12}$ ergs cm$^{-2}$ s$^{-1}$) | Luminosity $(10^{42}$ ergs s$^{-1}$) | Power Law Flux $(10^{-12}$ ergs cm$^{-2}$ s$^{-1}$) | Luminosity $(10^{42}$ ergs s$^{-1}$) |
|------------|---------------------------------------------|---------------------------------|---------------------------------------------|---------------------------------|
|            | Col. (1)                                    | Col. (2)                        | Col. (3)                                    | Col. (4)                        |
| B2 0055+30 | ...........                                | 0.88                            | 0.72                                        | 0.84                            |
| 3C 31      | ...........                                | 0.14                            | 0.08                                        | 0.10                            |
| 3C 66B     | ...........                                | 0.23                            | 0.27                                        | 0.21                            |
| 3C 84      | ...........                                | 14.10                           | 12.40                                       | 11.10                           |
| B2 0755+37 | ...........                                | 0.39                            | 1.73                                        | 0.35                            |
| 3C 264     | ...........                                | 2.24                            | 2.35                                        | 2.12                            |
| 3C 270     | ...........                                | 0.59                            | 0.11                                        | 0.49                            |
| 3C 272.1   | ...........                                | 0.16                            | 0.01                                        | 0.14                            |
| 3C 274.0   | ...........                                | 7.28                            | 0.32                                        | 3.76                            |
| 3C 317     | ...........                                | 0.22                            | 0.60                                        | 0.20                            |
| 3C 338     | ...........                                | 4.45                            | 9.57                                        | 1.66                            |
| 3C 346     | ...........                                | 0.48                            | 31.05                                       | 0.47                            |
| 3C 348     | ...........                                | 0.04                            | 4.78                                        | 0.04                            |
| 3C 449     | ...........                                | 0.17                            | 0.16                                        | 0.09                            |
| 3C 465     | ...........                                | 0.32                            | 1.18                                        | 0.25                            |

| Source     | Upper Limits $3\sigma$                     | Luminosity $(10^{42}$ ergs s$^{-1}$) |
|------------|---------------------------------------------|---------------------------------|
| 3C 28      | 0.18                                         | <0.03                           |
| B2 0120+33 | 0.25                                         | <0.01                           |
| B2 0149+35 | 2.36                                         | <0.23                           |
| B2 1257+28 | 0.06                                         | <0.01                           |
| B2 1346+26 | 0.68                                         | <0.03                           |
| 3C 348     | 0.09                                         | <0.01                           |
| 3C 449     | 0.07                                         | <0.05                           |
| 3C 465     | 0.03                                         | <0.01                           |

**Notes:** Col. (1): Source name. Cols. (2) and (3): Observed total flux and intrinsic luminosity in 0.3–8 keV of the source. Cols. (4) and (5): Observed flux and intrinsic luminosity in 0.3–8 keV for AGNs.

### TABLE 7
**Correlation Probabilities and Parameters**

| Correlation   | $P_r$ (%) | $|r|$ | $a$ | $b$ |
|---------------|-----------|------|-----|-----|
| Angle/log $N_{20}$ | 33.9      | 0.36 | 20.930 | 0.005 |
| log $v_{X,L_{20}}$/log $N_{20}$ | 52.8      | 0.21 | 22.984 | -0.044 |
| Angle/log $v_{X,L_{20}}$ | 42.4      | 0.22 | 42.937 | -0.025 |
| log $v_{X,L_{20}}$/log $v_{X,L_{20}}$ | 6.8E-4 | 0.89 | 8.596 | 0.826 |
| log $v_{D,L_{20}}$/log $v_{X,L_{20}}$ | 6.2E-3 | 0.85 | 0.427 | 1.002 |

**Detections Only**

**Detected + Upper Limits**

| Angle/log $v_{X,L_{20}}$ | 13.5      | ... | 42.519 | -0.018 |
| log $v_{D,L_{20}}$/log $v_{X,L_{20}}$ | 0.0      | ... | 5.101  | 0.911  |
| log $v_{D,L_{20}}$/log $v_{X,L_{20}}$ | 0.0      | ... | -1.253 | 1.039  |
(Harris 2003). On the other hand, 3C 270 appears to have an excess of X-ray flux for its given inclination, supporting our previous claims that the bulk of the X-ray emission originates from the accretion flow (Gliozzi et al. 2003).

It is worth noting that several issues can affect the angle-to-$L_X$ correlation, as well as the angle-to-$N_H$ correlation: (1) Uncertainties on the angles, which are rarely reported in the literature or are poorly determined. This is shown, for example, by a detailed study of VLBI observations of a complete sample of radio galaxies from the B2 and 3CR catalogs (Giovannini et al. 2001), in which the errors range from a few to dozens of degrees. (2) Beaming effects, which should not play an important role at relatively large angles. (3) The possible concentration of obscuring material on the equatorial plane, which can cause an intrinsically isotropic emission to appear anisotropic. For these reasons the origin of the X-ray radiation, that is, the fraction of X-rays produced by the jet and by the accretion process, remains an open question.

6. DISCUSSION

6.1. Obscuration in FR I Galaxies

An intriguing result of this paper is the finding that FR I galaxies have little or no excess X-ray absorption in their cores.
This result fits into the current debate, sparked by recent optical results, of whether or not low-power radio galaxies have an obscuring pc-scale torus. As mentioned earlier, HST images showed the presence of a compact core in the majority of 3C and B2 FR I galaxies (CH99, CA02). However, based on the same data, it was argued by Cao & Rawlings (2004) that a standard torus is indeed present in FR I galaxies, obscuring most of the isotropic radiation from the nucleus, and that the detected unresolved optical core is the emission of the jet on scales of tens of parsecs. The Chandra and XMM-Newton data support the conclusions of CH99 that no parsec-scale torus is present in FR I galaxies.

We now examine the possibility that the direct X-ray emission from the core is blocked by a Compton-thick torus ($N_{\text{HI}} > 10^{24} \text{ cm}^{-2}$), and that the measured X-ray radiation is due to reflection toward the observer by a “mirror” located above the torus, as postulated for Seyfert 2 galaxies (e.g., Matt et al. 2000). In this case, the values of $N_{\text{HI}}$ in Table 5 would not be associated with the torus, and an alternative explanation would have to be found.

To test the Compton-thick torus hypothesis, we calculated for each source of our sample the ratio $T = L_{\text{X}}/L_{\text{O mm}}$, where $L_{\text{X}}$ is the unabsorbed 2–10 keV luminosity of the CCCX and $L_{\text{O mm}}$ is the dereddened $O$ mm luminosity from the literature. The latter is produced in the narrow-line region and is considered a good indicator of the intrinsic AGN power. The average value for our FR I galaxy sample is $T_{\text{FR I}} = 34.4 \pm 8.0$, where the uncertainty is the standard dispersion. The average value of $T$ for the FR I galaxies of our sample was compared with the value derived for a sample of nine Seyfert 1 galaxies and for a sample of 16 Compton-thick Seyfert 2 galaxies. The data were derived from Nandra et al. (1997), Bassani et al. (1999), and Ho & Peng (2001). We find $T_{\text{Seyf 1}} = 37.8 \pm 9.6$ and $T_{\text{Seyf 2}} = 3.7 \pm 1.1$. The average $T$ for the FR I galaxies of our sample is much larger than in Compton-thick Seyfert 2 galaxies and is actually consistent with Seyfert 1 galaxies. This result supports the idea that FR I radio galaxies lack a Compton-thick torus.

The detection of the compact X-ray core is not correlated with the presence of a dust lane. In fact, dust lanes are equally present in sources with ($\approx 55\%$) and without ($\approx 45\%$) a CCCX in our sample (de Koff et al. 2000; de Ruiter et al. 2002). In the cases in which excess absorption is detected in the X-ray spectra and a dust lane is present, the column density from the X-rays and that due to the gas in the lane, $N_{\text{HI}}$, are different. More precisely, comparing the values of $N_{\text{HI}}$ from de Koff et al. (2000) and de Ruiter et al. (2002) to the values of $N_{\text{HI}}$ in Table 5, we find that the former is always $\approx 1$ order of magnitude smaller than the latter. This discrepancy was already reported previously for 3C 270 (e.g., Chiaberge et al. 2003a) and is known to exist for other AGNs (Maiolino et al. 2001). There are two possible interpretations: either the ratio of gas-to-dust in AGNs is different than in the Galaxy (Maiolino et al. 2001), or the optical and X-ray extinction occur in distinct media (Weingartner & Murray 2002). The latter hypothesis was suggested by us for 3C 270 (Sambruna et al. 2003).

Thus, we conclude that FR I galaxies lack a standard molecular torus, confirming the optical results. As discussed by CH99 and other authors, this implies that the lack of broad optical lines in these sources cannot be due to obscuration but is instead due to the absence of ionizing UV radiation, indicating inefficient accretion. Alternatively, the torus in FR I galaxies may have a much smaller opening angle than in FR II galaxies and/or lack significant cold gas. A survey of low-power radio galaxies in the far-IR can also probe the presence of obscuration in the cores of these sources independently.

### 6.2. Origin of the X-Rays in FR I Galaxies

The origin of the X-rays in radio galaxies in general, and in FR I galaxies in particular, is still matter of considerable debate. The strong correlation between radio and X-ray core luminosities observed in low-luminosity (e.g., Fabbiano et al. 1984; Canosa et al. 1999) and high-luminosity (e.g., Worrall & Birkinshaw 1994; Hardcastle et al. 1998) radio galaxies has often been used to argue in favor of a common origin from the unresolved base of the jet. However, such a correlation does not necessarily imply a common origin for the radiation in the X-ray and radio regimes. Indeed, accretion processes and relativistic jets are widely believed to be correlated phenomena (e.g., Begelman et al. 1984), and thus a correlation between jet and accretion-related fluxes is naturally expected. In fact, Merloni et al. (2003) have recently demonstrated that the correlation between X-ray and radio fluxes derives from a more general correlation (although with a substantial scatter) also involving the black hole masses (the so-called “fundamental plane”), in which the radio is produced by the jet, whereas the X-rays are likely to be related to a radiatively inefficient accretion flow.

Previous studies of low-power AGNs with Chandra demonstrate the importance of X-rays to making progress in this field (e.g., Di Matteo et al. 2001, 2003; Pellegrini et al. 2003; Terashima & Wilson 2003). However, despite the high-quality data provided by Chandra, the nature of the central engine in low-power AGNs is still poorly known. Some authors (e.g., Fabbiano et al. 2003; Pellegrini et al. 2003) favor a jet-dominated scenario, where the entire spectral energy distribution (SED) can be explained in terms of nonthermal emission from the unresolved base of a jet. Others (e.g., Di Matteo et al. 2003; Ptak et al. 2004) favor a radiatively inefficient scenario in which two solutions are possible: (1) a high accretion rate $M$ (of the order of $M_{\text{Bondi}}$) coupled with an extremely low radiative efficiency (basic ADAF scenario; see, e.g., Narayan 2002) or (2) a moderate $M$ ($\ll M_{\text{Bondi}}$) combined with a moderately low efficiency (more general RIAF scenario; see, e.g., Quataert 2003).

One of the reasons for this controversy is the poor discriminating power of the low-power AGNs’ spectral data, which does not allow one to choose between the competing scenarios. In order to break this spectral degeneracy, additional model-independent constraints are required. Such information can be provided by the X-ray temporal and spectral variability properties, as well as by energetic considerations derived from the radio jet. This is the approach adopted by Gliozzi et al. (2003) to investigate the origin of the X-rays in the nuclear region of the nearby 3C 270. They found that the bulk of the X-ray emission originates from a radiatively inefficient accretion flow, with negligible jet contribution.

On the other hand, in this paper we find a correlation between the X-ray core flux of FR I galaxies and the inclination angle of the jet. The trend is of decreasing X-ray luminosity with increasing orientation angle. This is expected if a fraction of the X-rays is beamed. It is thus possible that both the jet and a (radiatively inefficient; see below) accretion flow contribute to the production of the X-rays, with variable relative contributions. In support of this hypothesis, we note that in Figure 6b 3C 270 has an excess of X-rays over what expected from the jet, while M87 has a strong deficit.

More insightful results can be obtained from the spatial analysis, owing to the unprecedented spatial resolution of Chandra, which allows us to disentangle the different components and to study the innermost region of the AGN. The first important result of this work is that a substantial fraction (9 out of 25) of
FR I radio galaxies do not show a pointlike component at a high significance level (see Table 3).

The lack of CCCXs among sources with an optical core may suggest a different origin between X-ray and optical emission. The latter was attributed to the base of the jet (CH99; Cao & Rawlings 2004). Further support to this hypothesis was lent by Kharb & Shastri (2004), who demonstrated the presence of a strong correlation between the optical pointlike emission and the radio core dominance. On the other hand, the X-rays could be entirely produced in a very inefficient accretion flow.

Alternatively, the X-rays originate from the base of the jet, as suggested by the correlation we find between inclination angle and X-ray flux (Fig. 6b). In this case, the lack of CCCXs in sources with optical cores would place interesting constraints on the energy of the relativistic electrons and/or on the jet magnetic field.

### 6.3. Accretion in FR I Galaxies

The nature of the accretion process taking place onto the black hole in the nuclei of FR I galaxies is another unanswered question. Previous studies of FR I galaxies at X-ray (e.g., Sambruna et al. 1999; Di Matteo et al. 2001, 2003; Gliozzi et al. 2003) favor an inefficient accretion process on the basis of the spectral energy distribution and energetic and temporal properties. However, for this specific sample of FR I galaxies Cao & Rawlings (2004), on the basis of HST observations and model-dependent theoretical considerations, have claimed that the accretion is efficient and takes place in form of a standard accretion disk (Shakura & Sunyaev 1973). A first model-independent way to test the nature of the accretion process at work in the FR I galaxy nuclei is based on the comparison between the Eddington and bolometric luminosities. In the following, we assume that the X-rays are due to the accretion process. The limits become even more severe if the X-rays are due in part or totally to the jet (see above).

The Eddington luminosity is readily obtained once the black hole mass is known. Luckily, the black hole masses of all the objects of our sample have been reported in the literature (see Table 1). The bolometric luminosity has been estimated from the X-ray luminosity of the CCCX (i.e., the X-ray luminosity of the power-law component) assuming the canonical bolometric correction of 10 (e.g., Elvis et al. 1994). Incidentally, we note that the bolometric luminosities derived in this way are fully consistent with those derived from optical luminosities by Marchesini et al. (2004). The values of $L_{bol}/L_{Edd}$ for our sample, reported in Table 8, are quite low, ranging between $2 \times 10^{-3}$ and $3 \times 10^{-8}$. These values are fully consistent with a radiatively inefficient scenario and are clearly inconsistent with a “standard” accretion disk, as in the case of Seyfert 1 galaxies, where the bolometric luminosity is a significant fraction (typically 10%-30%) of the Eddington value.

An alternative model-independent method to assess the efficiency of the accretion process in FR I galaxies is based on the direct estimate of the radiative efficiency, $\eta$. This quantity can be readily obtained from the formula $L_{bol} = \eta M_{accer} c^2$, where a rough estimate of the accretion rate is given by the Bondi accretion rate $M_{Bondi} = 4\pi R_s^2 \rho_s c_s$, with accretion radius $R_s \sim GM/c_s^2$, $c_s$ the sound speed, and $\rho_s$ the density at the accretion radius. The value of $\rho_s$ can be derived either from a spatial method based on the deprojection of the surface brightness profile or from spectral method, which makes use of the normalization of the thermal spectral component (see, e.g., Gliozzi et al. 2003,
2004 for a detailed description of either method). For Chandra observations with good-quality brightness profiles, extending close to $R_e$ the spatial method gives the most reliable results. On the other hand, for XMM-Newton observations the spectral method is preferable. The values of $M_{\text{Bondi}}$ and $\eta$ are reported in Table 8, and provide further support to the hypothesis that the accretion in FR I galaxies is radiatively inefficient if X-rays come from accretion flow. To visualize the results we plot the histogram of the accretion rate in Eddington units in Figure 7. The Eddington accretion rate has been inferred assuming a canonical radiative efficiency of 0.1.

The only source with $\eta$ marginally consistent with the standard accretion rates is 3C 28. However, in this case, as for all the sources listed as “Undetected CCCX” in Table 8, the values reported must be considered carefully. For this source there is not a CCCX detection and an upper limit of the X-ray luminosity has been used in the evaluation of $L_{\text{bol}}$ and $\eta$.

7. SUMMARY

We have presented Chandra and XMM-Newton observations of FR I galaxies from the 3CR and B2 catalogs, for which there are high-quality HST observations. The main findings of this paper can be summarized as follows:

1. A thorough spatial analysis reveals that 13 out of the 25 objects in the sample exhibit an X-ray central compact core (CCCX); for three of the sources the detection of a CCCX is uncertain, and for the remaining nine sources no CCCX is found. All sources with a compact X-ray core also possess a compact core in the optical; however, some sources with an optical core lack a CCCX.

2. All the FR I galaxies are embedded in an extended component, which is fit by at least one $\beta$-model with parameters typical for a host galaxy and/or for an intracluster medium.

3. The results from the spectral analysis are in good agreement with the spatial analysis. All the CCCX spectra are well fit by power laws with photon indices $\Gamma \sim 1.1-2.6$ and at least one thermal component at softer energies. The remaining sources require only thermal components.

4. Among the sources with a CCCX, intrinsic absorption over the Galactic value is required in only eight cases, with $N_{\text{HI}} \sim 10^{21}-10^{23}$ cm$^{-2}$. This result, combined with model-independent tests, supports the previous claim (e.g., Chiaberge et al. 1999) that low-power radio galaxies lack a standard molecular torus on parsec scales. As a consequence, the nondetection of CCCXs cannot be attributed to obscuration effects, but rather to the intrinsic weakness of the AGN component.

5. The origin of the X-rays (i.e., jet vs. accretion) is still an open question. On the one hand, the nondetection of a CCCX in objects with an optical CCC (interpreted as jet radiation) may indicate a different origin for X-ray and optical emission. On the other hand, the correlation between the Chandra X-ray luminosity and the inclination angle of the jet suggests that at least a fraction of the X-ray emission originates in the jet. However, the accretion flow can still play a role in the production of the X-rays in individual sources, as shown by our previous analysis of 3C 270.

6. If the detected X-ray luminosities are considered as an upper limit on the isotropic component, stringent limits on the Eddington ratios $L_{\text{bol}}/L_{\text{Edd}}$ and on the accretion efficiency $\eta$ can be derived, with $L_{\text{bol}}/L_{\text{Edd}} \sim 10^{-3}$ to $10^{-8}$ and $\eta \sim 10^{-2}$ to $10^{-6}$, suggesting radiatively inefficient accretion. The upper limits are even lower if part or all the X-rays are due to the jet.

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