XMM-NEWTON OBSERVATIONS OF THE NUCLEI OF THE RADIO GALAXIES 3C 305, DA 240, AND 4C 73.08

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ABSTRACT

We present new XMM-Newton EPIC observations of the nuclei of the nearby radio galaxies 3C 305, DA 240, and 4C 73.08, and investigate the origin of their nuclear X-ray emission. The nuclei of the three sources appear to have different relative contributions of accretion- and jet-related X-ray emission, as expected based on earlier work. The X-ray spectrum of the FR II narrow-line radio galaxy (NLRG) 4C 73.08 is modeled with the sum of a heavily absorbed power law that we interpret to be associated with a luminous accretion disk and circumnuclear obscuring structure, and an unabsorbed power law that originates in an unresolved jet. This behavior is consistent with other narrow-line radio galaxies. The X-ray emission of the low-excitation FR II radio galaxy DA 240 is best modeled as an unabsorbed power law that we associate with a parsec-scale jet, similar to other low-excitation sources that we have studied previously. However, the X-ray nucleus of the narrow-line radio galaxy 3C 305 shows no evidence for the heavily absorbed X-ray emission that has been found in other NLRGs. It is possible that the nuclear optical spectrum in 3C 305 is intrinsically weak-lined, with the strong emission arising from extended regions that indicate the presence of jet-environment interactions. Our observations of 3C 305 suggest that this source is more closely related to other weak-lined radio galaxies. This ambiguity could extend to other sources currently classified as NLRGs. We also present XMM-Newton and VLA observations of the hot spot of DA 240, arguing that this is another detection of X-ray synchrotron emission from a low-luminosity hot spot.

Subject headings: galaxies: active — galaxies: individual (3C 305, 4C 73.08, DA 240) — galaxies: jets

1. INTRODUCTION

Radio galaxies consist of twin jets of particles that are ejected from a compact region in the vicinity of a supermassive black hole, feeding into large-scale “plumes” or “lobes.” There are two principal morphological classes of radio galaxies, low-power (Fanaroff-Riley type I, hereafter FR I) sources and high-power (FR II) sources Fanaroff & Riley (1974). FR I sources exhibit “edge-darkened” large-scale radio structure, and modeling implies that initially supersonic jets in these sources decelerate to transonic speeds on roughly kiloparsec scales before flaring into large plumes (e.g., Perucho & Martí 2007). FR II sources appear “edge-brightened,” and in these cases highly supersonic jets propagate out to large distances (often > 100 kpc) from the core before terminating in bright hot spot and accompanying radio lobes. Observationally, the Fanaroff-Riley divide occurs at a 178 MHz radio power of ~10^23 W Hz^{-1} sr^{-1}.

It is important to understand whether the kiloparsec-scale Fanaroff-Riley dichotomy is determined by the interaction between the jet and its external hot-gas environment (e.g., Bicknell 1995), or rather is nuclear in origin and governed by differences in the properties of the accretion flow (Reynolds et al. 1996). The first observations of large samples of z < 0.1 3CRR radio-galaxy nuclei with Chandra and XMM-Newton (Donato et al. 2004; Balmaverde et al. 2006; Evans et al. 2006) showed that FR I nuclei show no signs of heavily absorbed X-ray emission that would be expected from standard AGN unification models (Urry & Padovani 1995), are dominated by emission from an unresolved jet (e.g., Worrall & Birkinshaw 1994; Balmaverde et al. 2006; Evans et al. 2006), and have highly radiatively inefficient accretion flows. Narrow optical-line FR II sources show evidence for heavily obscured (N_H > 10^{23} cm^{-2}) nuclear X-ray emission that is associated with a radiatively efficient accretion flow, together with an unabsorbed component of jet-related emission (Evans et al. 2006; Hardcastle et al. 2006). FR II radio galaxies at higher redshift are consistent with such behavior (Belsole et al. 2006).

A significant breakthrough for understanding the physical origin of the FR I/FR II dichotomy came from Chandra and XMM-Newton observations of the population of low-excitation radio galaxies (LERGs), which have weak or no emission lines in their optical spectra (Hine & Longair 1979; Jackson & Rawlings 1997). Almost all FR I radio galaxies are LERGs, but there is a significant population of FR II LERGs at 0.1 < z < 0.5. The X-ray spectra of LERGs, irrespective of their FR I or FR II morphology, are dominated by unabsorbed emission that can be associated with a parsec-scale jet, with no obvious contribution from accretion-related emission. These sources are likely to accrete in a radiatively inefficient manner (Hardcastle et al. 2006). On the other hand, high-excitation radio galaxies (HERGs—i.e., NLRGs, BLRGs, and quasars), which display prominent narrow or broad optical emission lines, have X-ray spectra that are consistent with standard unification models: they show evidence for luminous, radiatively efficient accretion disks, together with circumnuclear tori when the source is oriented close to edge-on with respect to the observer. HERGs tend to show evidence for additional hot dust over and above that of LERGs in their mid-IR spectra (e.g., Ogle et al. 2006; M. Birkinshaw et al., in preparation), which is again consistent with reprocessing of luminous accretion-related emission by torus-like structure. Most high radio-power (FR II)
NUCLEI OF 3C 305, DA 240, AND 4C 73.08

TABLE 1

| Source        | Redshift | FR Classification | Optical Excitation | Optical Spectrum Reference | 178 MHz Luminosity Density (W Hz\(^{-1}\) sr\(^{-1}\)) | Galactic Absorption (cm\(^{-2}\)) |
|---------------|----------|------------------|-------------------|----------------------------|-----------------------------------------------|---------------------------------|
| 3C 305        | 0.0416   | I                | NLRG              | Liu & Kennicutt (1995)     | 5.50 \times 10^{24}                           | 1.69 \times 10^{20}             |
| DA 240        | 0.0356   | II               | LERG              | Saunders et al. (1989)     | 5.38 \times 10^{24}                           | 4.36 \times 10^{20}             |
| 4C 73.08      | 0.0581   | II               | NLRG              | Saunders et al. (1989)     | 9.94 \times 10^{24}                           | 2.33 \times 10^{20}             |

solutions are high-excitation radio galaxies. The distinct X-ray nuclear properties of low- and high-excitation radio galaxies, regardless of their large-scale FR I or FR II morphology, could be interpreted as implying that the Fanaroff-Riley dichotomy remains principally influenced by jet power and environment. The excitation dichotomy, on the other hand, is interpreted to be attributed to the radiative efficiency of the accretion flow (e.g., Hardcastle et al. 2006) and possibly related to the nature of the accreting material (Hardcastle et al. 2007b).

Here, we report new XMM-Newton observations of the nuclei of three \(z < 0.1\) 3CRR radio galaxies—3C 305, DA 240, and 4C 73.08. The three sources have \(178\) MHz radio powers that lie close to the FR I/FR II dividing luminosity (Table 1), plus a range of radio morphologies and optical emission-line characteristics. They are therefore good candidates for examining possible connections between the central engine and large-scale radio characteristics. This paper is organized as follows. In § 2 we describe the optical and radio properties of the three sources. Section 3 contains a description of the data and a summary of our analysis. In § 4 we report the results of our spectroscopic analysis of the sources. In § 5 we describe VLA and XMM-Newton observations of the bright northeast hot spot in DA 240. In § 6 we interpret the observations in the context of our previous Chandra and XMM-Newton observations of 3CRR radio galaxies and discuss the optical emission-line characteristics of the sources. We end with our conclusions in § 7. All results presented in this paper use a cosmology in which \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\). Errors quoted in this paper are 90% confidence for one parameter of interest (i.e., \(\chi^2_{\min} + 2.7\)), unless otherwise stated.

2. OVERVIEW OF THE SOURCES

2.1. 3C 305

3C 305 is \(z = 0.0416\) \(d_L = 183\) Mpc narrow-line radio galaxy (Laing et al. 1983) with an unusually compact radio morphology that displays both FR I and FR II characteristics. MERLIN and VLA observations of the source (Heckman et al. 1982; Jackson et al. 2003; Morganti et al. 2005) show twin jets that each extend into radio lobes separated by \(\sim 4''\) (3.3 kpc). Laing et al. (1983) classify the source as a FR I-type radio galaxy. Optical emission-line studies of the circumnuclear environment of 3C 305 show an extended morphology (Heckman et al. 1982; Jackson et al. 1995), and a detailed comparison between the radio ejecta and [O ii] gas observed with HST (Jackson et al. 1995) suggests that the gas has been shocked by the jet.

2.2. DA 240

DA 240 \((z = 0.0356, d_L = 157\) Mpc) is a giant radio galaxy (GRG), the name given to the subclass of FR II sources with a projected radio extent in excess of 1 Mpc. Westerbork Synthesis Radio Telescope (WSRT) images of the source (Klein et al. 1994; Peng et al. 2004) show two hot spot, with the northeastern one 50 times brighter than the southwestern one. The northeastern hot spot has an unusual bifurcated structure, with what appears to be a radio jet entering a compact, primary hot spot, together with a fainter secondary hot spot feature. Optically, DA 240 is classified as a low-excitation radio galaxy (Laing et al. 1983).

2.3. 4C 73.08

4C 73.08 \((z = 0.0581, d_L = 258\) Mpc) is another example of an FR II GRG. WSRT images (Mayer 1979; Klein et al. 1994) show a compact core accompanied by two hot spots. The brighter (western) hot spot is connected to the core by a bridge of radio emission. Both lobes show unusual protrusions toward the north and south. Optically, 4C 73.08 is classified as a narrow-line radio galaxy (Laing et al. 1983).

A summary of the properties of the three sources is given in Table 1.

3. OBSERVATIONS AND DATA REDUCTION

XMM-Newton observed 3C 305, DA 240, and 4C 73.08 as part of AO-5. We reprocessed the data with version 7.1.0 of the Scientific Analysis Software (SAS) using the standard pipeline tasks emchain and ephchain. The data were filtered for PATTERN values \(\leq 12\) (MOS) and \(\leq 4\) (pn) and the bit-mask flags 0x766a0600 (MOS) and 0xfa000c (pn). These flag sets are equivalent to the standard flag sets #XMMEE_EM/EP but include out of field of view events and exclude bad columns and rows.

To check for intervals of high particle background, we extracted light curves from the CCD on which the source is located. The events were filtered to include only those with PATTERN = 0 attributes and an energy range of 10–15 keV. The background was relatively low during the observations of 3C 305 and DA 240, meaning that no further filtering was required, especially given that we are performing spectral analyses of point sources. However, the observation of 4C 73.08 was heavily affected by flaring for almost the entire duration of the observation; indeed the MOS observation was truncated due to high background. We therefore chose filtering criteria of \(< 2.5\) s\(^{-1}\) (MOS) and \(< 2.5\) s\(^{-1}\) (pn) in the 10–15 keV band to remove the worst flaring but retain sufficient data to perform spectroscopy. Table 2 gives the details of the three XMM-Newton observations. All spectral fits include Galactic absorption.

The unresolved nuclei of all three sources are detected with XMM-Newton; in addition, there is a weak but clear detection of an X-ray source coincident with the bright northeast hot spot of DA 240. We discuss the analysis of these X-ray features in the following two sections.

4. SPECTROSCOPIC ANALYSIS OF THE NUCLEI

4.1. 3C 305

We extracted the nuclear X-ray spectrum of 3C 305 from a source-centered circle of radius 35\(^{\prime\prime}\), with background sampled from a large off-source region on the same CCD as the target.
There were sufficient counts in the spectra from each of the MOS1, MOS2, and pn cameras to perform a joint analysis for all three data sets. The spectra were grouped to a minimum of 20 counts per bin.

We initially attempted to fit the spectrum with a single, unabsorbed power law, but this achieved a poor fit ($\chi^2 = 68.0$ for 33 dof). We found an acceptable fit ($\chi^2 = 29.3$ for 31 dof) with the combination of an unabsorbed power law and thermal emission, characterized by an APEC model with $kT = 0.69^{+0.10}_{-0.15}$ keV, abundance fixed at 0.3 times solar, and normalization $(3.78^{+1.56}_{-0.67}) \times 10^{-5}$ photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$. The best-fitting parameters of the power law are $\Gamma = 1.61^{+0.37}_{-0.38}$ and 1 keV normalization $(1.45^{+0.44}_{-0.18}) \times 10^{-5}$ photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$. Adding additional components, such as allowing the power law to be modified by additional absorption, failed to improve the fit (the best-fitting intrinsic absorption tended to zero). The thermal interpretation is supported by a Chandra observation of the source (PI: D. Harris), which shows resolved emission elongated $\sim 3''$ either side of the nucleus along the direction of the jets. Indeed, the unresolved Chandra nuclear flux is 3 times lower than that which we measured with XMM-Newton. The XMM-Newton spectra and best-fitting model are shown in Figure 1.

### 4.2. DA 240

We extracted the spectrum of the nucleus of DA 240 from a source-centered circle of radius $35''$, and extracted a background spectrum from a large off-source circular region on the same chip. Only the spectrum from the pn camera had sufficient counts for an adequate spectral analysis. With the data grouped to 10 counts per bin, we found an acceptable fit ($\chi^2 = 10.5$ for 9 dof) with a single unabsorbed power law of photon index $1.91^{+0.54}_{-0.34}$ and 1 keV normalization $(6.48^{+1.48}_{-0.51}) \times 10^{-6}$ photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$. Allowing the power law to be modified by intrinsic absorption failed to improve the fit (the best-fitting $N_{\text{H}}$ is zero). Additional components to our model also led to no statistically significant improvement in the fit. The spectrum, and best-fitting model, of a single, unabsorbed power law, are shown in Figure 2.

### 4.3. 4C 73.08

We sampled the nuclear spectrum of 4C 73.08 from a source-centered circle of radius $35''$, and extracted a background spectrum from a large off-source circular region on the same chip. We initially attempted to model the spectrum with a single, unabsorbed power law, but this achieved a poor fit ($\chi^2 = 63.2$ for 15 dof), and we noticed significant residuals above $\sim 4$ keV that clearly indicated the presence of an additional, highly absorbed component. We achieved a good fit ($\chi^2 = 7.2$ for 11 dof) to the spectrum with the sum of a heavily absorbed $[N_{\text{H}} = (9.2^{+5.4}_{-2.7}) \times 10^{22}$ cm$^{-2}$] power law of photon index frozen at 1.7, a Gaussian neutral, unresolved, Fe K$\alpha$ line of equivalent width $\sim 300$ eV (the Gaussian line is significant at the 2 $\sigma$ level), and a second, unabsorbed, power law of photon index frozen at 2. There are insufficient counts to fit the power-law slopes, so we adopted values consistent with canonical values found in radio galaxies (e.g., Evans et al. 2004, 2006). The 1 keV normalizations of the power laws are $(1.82^{+1.29}_{-1.00}) \times 10^{-3}$ photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$ and $(1.90 \pm 0.47) \times 10^{-5}$ photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$, respectively. Replacing the unabsorbed power law with a thermal component resulted in a worse fit to the spectrum ($\chi^2 = 16.9$ for 10 dof).
The spectrum and our best-fitting model are shown in Figure 3. The hot spot of 4C 73.08 is not detected in this short observation.

Table 3 summarizes the best-fitting spectral models to the X-ray spectra of 3C 305, DA 240, and 4C 73.08.

5. THE HOT SPOT OF DA 240

The bright northeast hot spot of the giant radio galaxy DA 240 lies in the XMM-Newton field of view and is clearly detected in X-rays in our observation (Fig. 4). X-ray detections of the hot spot in relative low-luminosity radio sources like our targets are quite common in Chandra observations (e.g., Kraft et al. 2005, 2007; Hardecastle & Croston 2005; Hardcastle et al. 2007a; Evans et al. 2008) and recently some bright hot spot have also been detected with XMM-Newton (Erlund et al. 2007; Goagor et al. 2008). It has been argued that X-ray detections of low-luminosity hot spot such as those of DA 240 (whose northeast hot spot has a 5 GHz radio luminosity of $9 \times 10^{22}$ W Hz$^{-1}$ sr$^{-1}$) are almost certainly due to synchrotron rather than inverse Compton emission (see Fig. 5 of Hardcastle et al. 2004). If this is the case, X-ray detections of hot spot can give us important information about the relationship between the location of high-energy particle acceleration (traced by the X-ray) and the locations where low-energy particle and field energy densities are highest (traced by the radio synchrotron emission). The available evidence to date is that this relationship is complex; kiloparsec-scale offsets are often found between the peaks of X-ray and radio emission (e.g., Hardcastle et al. 2007a).

The only radio image for DA 240 available to us at the start of our study was the WSRT 608 MHz image from the online atlas of low-$z$ 3CRR sources. This image has a resolution of $34''$, and so does not allow us to see details of the hot spot structure or its relationship to the X-ray emission. Accordingly we obtained a short observation of the hot spot with the VLA at 4.9 GHz under the exploratory time program. This observation (observation identifier AE163) was taken on 2007 May 18 when the VLA was in the process of moving between its D and A configurations. In addition, the EVLA antennas of the array were unavailable for most of the observation. As a result there were only 13 antennas available in the expected D-configuration arrangement, as opposed to the usual 27. Nevertheless we obtained an image with a resolution of $7.5''$ and were able to detect and resolve the compact hot spot (Fig. 5). The radio emission coincident with the X-ray emission is resolved into two compact components aligned

![Fig. 3.—XMM-Newton pn spectrum of 4C 73.08. Also shown is the best-fitting model of a heavily absorbed power law, a neutral Fe Kα line, and a second, unabsorbed power law.](image)

![Fig. 4.—XMM-Newton observations of DA 240 in the MOS and pn cameras, co-added taking account of exposure and smoothed with a Gaussian of FWHM = 15.3''. Overlaid are contours from the 34'' resolution 608 MHz WSRT map described in the text, at $2 \times (1, 4, 16, \ldots)$ mJy beam$^{-1}$.](image)

### Table 3

| Source | Spectrum | $N_H$ (cm$^{-2}$) | $\Gamma$ | $E$ (keV) | $\sigma$ (keV) | $kT$ (keV) | $L_{(1-10 keV)}$ (Power Law) | $\chi^2$/dof |
|--------|----------|-----------------|---------|----------|--------------|-----------|-----------------------------|-------------|
| 3C 305 | PL+TH    | $\ldots$        | $1.61^{+0.37}_{-0.38}$ | $\ldots$ | $0.61^{+0.10}_{-0.15}$ | $2.6 \pm 0.8 \times 10^{41}$ | 29.3/31 |
| DA 240 | PL       | $1.91^{+0.54}_{-0.31}$ | $\ldots$ | $\ldots$ | $(5.5 \pm 1.3) \times 10^{40}$ | 10.5/9 |
| 4C 73.08 | $N_0(\text{PL+Gauss})+\text{PL}$ | $(9.2^{+1.5}_{-1.4}) \times 10^{23}$ | $\Gamma_1 = 1.7 (f)$; $\Gamma_2 = 2 (f)$ | $6.32 \pm 0.14$ | $0.01 (f)$ | $\ldots$ | $(5.7^{+0.2}_{-0.6}) \times 10^{43}$ | 7.2/11 |

Notes.—Col. (1): Name of source. Col. (2): Description of best spectrum ($N_H =$ intrinsic absorption, PL = power law, Gauss = redshifted Gaussian line, TH = thermal. Col. (3): Intrinsic neutral hydrogen column density. Galactic absorption has also been applied. Col. (4): Power-law photon index. Col. (5): Rest-frame Gaussian centroid energy. Col. (6): Gaussian line width. Col. (7): Temperature of thermal component. Col. (8): 2–10 keV unabsorbed luminosity of primary power law. Col. (9): Value of $\chi^2$ and degrees of freedom. The notation (f) indicates that parameter was frozen.

5 See http://www.jb.man.ac.uk/atlas.
roughly north-south, with the brighter southern component having a radio flux density of 270 mJy and the fainter northern component at a level of ~90 mJy, plus extended structure. Both the compact components are pointlike at the resolution of our image; however, higher resolution images (Tsien 1982) resolve the southern component, showing it contains at least two separate peaks. The peak of the X-ray emission is closest to the brighter component of the hot spot, but both components may be X-ray sources: the resolution of XMM-Newton is not good enough (particularly at this off-axis distance) to separate them. We used the default astrometry for both the VLA and XMM-Newton data to search for offsets between the radio and X-ray emission in the northern hot spot (the radio core is too far down the primary beam of the VLA for us to be able to use it to align the radio and X-ray frames). The X-ray emission appears to be offset by several kpc approximately in the direction of the nucleus. However, the higher resolution radio observation of Tsien (1982) shows that the brightest radio subcomponent (marked A by Tsien et al.) is separated by approximately 8″ (~5.5 kpc) from the brightest X-ray emission. Offsets this large, or larger, have been observed in other powerful radio galaxies (e.g., Erlund et al. 2007).

We extracted a spectrum for the hot spot from the pn data, using a 30″ radius circle as the source region and local background, and fitted it with a power-law model with Galactic absorption. It is well fitted ($\chi^2 = 0.29$ for 2 dof) with a model with photon index of $2.2 \pm 0.3$ and 1 keV unabsorbed flux density of $7 \pm 1$ mJy. This flux density puts it among the brighter known X-ray hot spots detected by Erlund et al. (2007) in the giant quasar 4C 74.26.

The steep X-ray spectrum and the possible offset between the radio and X-ray peak favor a synchrotron rather than inverse Compton origin for the X-rays in this source. In the absence of optical measurements it is easy to fit a curved or broken synchrotron spectrum through the radio and X-ray data. Moreover, if we model the hot spot (normalizing using the observed radio flux for the brighter component) as a uniform sphere at equipartition with a radius of 1 kpc (which is consistent with the size reported by Tsien [1982] for the most compact component of the hot spot only) then the predicted inverse Compton flux density, using the code of Hardcastle et al. (1998) is 3 orders of magnitude below that observed. All of the flux density from the hot spot would have to come from a region <0.1 pc in size, the magnetic field strength would have to be a factor ~30 below the equipartition value, or some combination of the two would have to apply in order for the observed X-ray flux density to be produced by the synchrotron self-Compton model. Since DA 240 is a low-excitation radio galaxy, the nuclear emission-line classification gives us no information about the orientation with respect to the line of sight, and so it is possible in principle that inverse Compton emission could be boosted by a process which requires beaming and small angles of the jet to the line of sight (e.g., Georgopoulous & Kazanas 2003). However, an efficient role for beaming would imply a very large physical size (~4 Mpc) for DA 240, so we do not regard this model as probable, and we attribute the X-ray emission to synchrotron radiation. The relative brightness of the hot spot should make it a good target for follow-up radio and high-resolution X-ray observations aimed at understanding the details of high-energy particle acceleration in this source.

6. INTERPRETATION OF THE NUCLEAR SPECTRA

6.1. Overview of the Spectra

The unabsorbed X-ray spectrum of the low-excitation FR II radio galaxy DA 240 is consistent with the other LERGs in the Hardcastle et al. (2006) sample, which observationally encompass both FR I and FR II radio galaxies. The high-excitation (narrow-line) FR II radio galaxy 4C 73.08 shows a heavily absorbed, luminous, component of X-ray emission, similar to the other narrow-line radio galaxies studied by Hardcastle et al. (2006). However, the spectrum of 3C 305 shows no evidence for the heavily absorbed X-ray emission that is characteristic of narrow-line radio galaxies. We return to this in § 6.4.

6.2. The Radio Core–X-Ray Core Correlation

Figure 6 shows a plot of the 1 keV luminosity of the low-absorption power-law component against the core luminosity for our three sources (Table 4), together with the 3CRR sources presented in Evans et al. (2006) and Hardcastle et al. (2006). DA 240 and 4C 73.08 both lie close to the correlation between the radio and X-ray luminosities established by, e.g., Fabbiano et al. (1984), Worrall & Birkinshaw (1994), and Hardcastle et al. (2006). On the other hand, 3C 305 lies somewhat away from the other data, although this is almost certainly due to the extended X-ray emission detected with Chandra. Indeed, the unresolved Chandra nuclear flux is 3 times lower than the XMM-Newton value, which would bring 3C 305 closer to established trend line in Figure 6. The radio–X-ray core correlation suggests a common origin of the two at the base of an unresolved jet, as has been extensively argued by, e.g., Worrall & Birkinshaw (1994), Hardcastle & Worrall (1999), Evans et al. (2006), Balmaverde et al. (2006), and Belsole et al. (2006).

6.3. Accretion-related X-Ray Emission

We now wish to consider any accretion-related X-ray emission. For 4C 73.08, as with the other narrow-line radio galaxies studied by Evans et al. (2006) and Hardcastle et al. (2006) we can take the accretion-related luminosity to be the unobscured luminosity of the heavily absorbed power-law component: this is supported by the presence of Fe Kα emission (e.g., Evans et al. 2006). The
2–10 keV accretion luminosity of 4C 73.08 (∼6 × 10^43 ergs s^{-1}) is substantially larger than its jet-related luminosity (∼4 × 10^41 ergs s^{-1}), as has been found with other NLRGs (e.g., Evans et al. 2006; Hardcastle et al. 2006).

In the cases of the LERG DA 240 and the (purported NLRG 3C 305), we followed the method of Evans et al. (2006) and assumed that, in addition to the dominant jet component of X-ray emission, there exists an additional “hidden” component of accretion-related emission of photon index 1.7 that is obscured by a torus of intrinsic absorption 10^{23} cm^{-2}. We added this component to the best-fitting model, refitted the spectra, and determined the 90% confidence upper limit to the 2–10 keV accretion-related luminosity to be 5.3 × 10^{41} ergs s^{-1} for DA 240 and 1.0 × 10^{42} ergs s^{-1} for 3C 305.

Figure 7 shows a plot of the 178 MHz and 2–10 keV accretion-related luminosities of the three sources, together with combined z < 0.5 sample (Evans et al. 2006; Hardcastle et al. 2006) as a function of 178 MHz total radio luminosity (Table 4). Symbols are as in Fig. 6. Dotted lines show the regression line to the NLRGs only and its 1 σ confidence range.

![Fig. 6.—X-ray luminosity of the unabsorbed nuclear component for the three sources, together with combined z < 0.5 sample (Evans et al. 2006; Hardcastle et al. 2006) as a function of 5 GHz radio core luminosity (Table 4). Open circles show LERGs, filled circles show NLRGs, open stars show BLRGs, and filled show stars quasars. Large surrounding circles indicate that a source is an FR I. The sources studied in this paper are indicated by surrounding boxes. Note that the core luminosity of 3C 305 is measured at 1.4 GHz. Where error bars are not visible they are smaller than symbols. Dotted lines show the best-fitting model, refitted the spectra, and determined the 90% confidence upper limit to the 2–10 keV accretion-related luminosity to be 5.3 × 10^{41} ergs s^{-1} for DA 240 and 1.0 × 10^{42} ergs s^{-1} for 3C 305.

Figure 7 shows a plot of the 178 MHz and 2–10 keV accretion-related luminosities of the three sources (Table 4), together with those of the other z < 0.5 3CRR sources studied by Evans et al. (2006) and Hardcastle et al. (2006). Figure 7 shows that the upper limit to the accretion-related components in the LERG DA 240, given our assumed absorbing column of 10^{23} cm^{-2}, lies below the trend line established for high-excitation (narrow-line) radio galaxies such as 4C 73.08. Of course, if no obscuring region is present in DA 240, as seems to be the case in other LERGs, then the luminosity of any accretion-related emission will be substantially lower than that shown. Alternatively, the accretion-related X-ray luminosity of LERGs can be made to lie in the region

![Fig. 7.—X-ray luminosity of the accretion-related component for the three sources, together with combined z < 0.5 sample (Evans et al. 2006; Hardcastle et al. 2006) as a function of 178 MHz total radio luminosity (Table 4). Symbols are as in Fig. 6. Dotted lines show the regression line to the NLRGs only and its 1 σ confidence range.

TABLE 4

| Source | Radio Core^a | 1 keV Soft | 178 MHz | 2–10 keV “Accretion” Luminosity | Core Luminosity Reference |
|--------|-------------|-----------|--------|-------------------------------|--------------------------|
|        | (1)         | (2)       | (3)    | (4)                           | (5)                      | (6)                      |
| 3C 305 | <3.21 × 10^20 (1.4 GHz) | (3.1 ± 0.9) × 10^{15} | 5.50 × 10^{24} | <1.0 × 10^{42} | Jackson et al. (2003) |
| DA 240 | 2.46 × 10^22 (5 GHz) | (1.4 ± 0.3) × 10^{15} | 5.38 × 10^{24} | <5.3 × 10^{41} | Tsien (1982) |
| 4C73.08 | 3.53 × 10^21 (5 GHz) | (4.1 ± 1.0) × 10^{15} | 9.94 × 10^{24} | (5.7^{+5}_{-3}) × 10^{43} | Saripalli et al. (1997) |

Notes.—Col. (1): Name of source. Col. (2): Radio luminosity density of core. Col. (3): 1 keV unabsorbed luminosity density of soft X-ray component. Col. (4): 178 MHz VLA luminosity density. Col. (5): 2–10 keV unabsorbed X-ray “accretion-related” luminosity. Obtained by direct fitting with free \( N_H \) (4C 73.08) and as a hidden component with \( N_H \) fixed at 10^{23} cm^{-2} (3C 305, DA 240). Col. (6): Reference for radio core luminosity density.

^a Frequency is given in parentheses.
occupied by the HERGs, but this requires extremely high values of intrinsic absorption (Evans et al. 2004) that can be ruled out by infrared observations (e.g., Müller et al. 2004). The upper limit to the accretion-related luminosity of 3C 305 lies between the populations of low- and high-excitation sources in Figure 7, although as previously mentioned the XMM-Newton-measured unresolved core flux is overestimated by a factor ~3 (see § 4.1).

6.4. Optical Emission Line Classifications and Relationships to the Central Engine

In our previous studies of the X-ray properties of 3CRR radio sources we have used the Laing et al. (1983) optical emission-line classifications of low- and high-excitation radio galaxies. Laing et al. (1994) provided a quantitative definition of LERGs as having \([\text{O}\,\text{iii}]\) equivalent widths of less than 3 Å and \([\text{O}\,\text{iii}]/H\alpha\) line ratios >0.2. A similar classification was given by Jackson & Rawlings (1997) with LERGs having \([\text{O}\,\text{iii}]\) equivalent widths of less than 10 Å and/or \([\text{O}\,\text{ii}]/\text{H}\beta\) line ratios >1. However, these definitions of low- and high-excitation sources do not necessarily take into account the potentially different sources of ionizing radiation, their size scale, or their relationship to the AGN itself. This may lead to occasional ambiguities where sources are classified based on their emission-line characteristics. We discuss some of the issues here.

\textit{HST} observations of the nuclei of radio galaxies have revealed the origin of the optical continuum emission and its likely relationship to any unresolved emission lines. In the case of LERGs, Chiaberge et al. (1999) and Hardcastle & Worrall (2000) showed that the correlations between the radio and optical continuum luminosities support the common origin of the two in the form of a jet.\textit{HST} narrowband imaging of LERGs (Capetti et al. 2005) showed that so-called compact emission line regions (CELRs) are commonplace, and that they are associated with the dominant source of ionizing photons, assumed to be the jet. Further, Chiaberge et al. (2002) argued that the dominant contribution to the optical emission in obscured high-excitation radio galaxies is the accretion disk. There is likely to be a substantial ionizing field in these sources that is directly related to the accretion process.

On larger scales, high-resolution \textit{HST} emission-line images of the extended environments in radio galaxies (Privon et al. 2008) provide insights on the different components that constitute the kiloparsec-scale narrow-line region (NLR) and \(\sim\)10 kpc scale extended narrow-line region (ENLR). In addition to photoionization from the nucleus, jet-environment interactions may play a significant role in governing the energy budget of the NLR and ENLR, either in the form of collisional ionization or a radiative “autoionizing” shock (e.g., Dopita & Sutherland 1995, 1996).

The different physical origins for optical line emission in radio galaxies illustrate the difficulties in disentangling genuine AGN emission from that which is not directly related to the accretion process. An excellent case in point is the purported NLRG 3C 305, whose X-ray spectrum is consistent with that of a LERG, rather than a NLRG. \textit{HST} [\text{O} II] observations of the extended emission-line environment in the source show that the majority of the [O II] emission lies just beyond the edge of the radio jet at a distance of 1.5\arcsec from the core, and Jackson et al. (1995) suggested that it has been shock-excited by the jet. Several other FR I radio sources studied by Evans et al. (2006) and Hardcastle et al. (2006) also show optical spectra that may be attributed to their environments. Some of these lie at the centers of cooling-core clusters, in which significant amounts of optical line emission might be expected that are not necessarily directly related to the central AGN. This may go some way to explaining the handful of other purported NLRGs in Figure 7 whose X-ray properties are more consistent with low-excitation sources.

The above arguments suggest that the emission-line classification of relatively weak-lined radio galaxies does not always reflect the nuclear accretion activity itself. We propose that only the combination of high-resolution optical spectroscopy, X-ray observations, and constraints from \textit{Spitzer} mid-infrared observations of reprocessed emission in radio galaxies can reliably determine the structure of the central engine in radio-loud AGNs. In the case of 3C 305, \textit{Spitzer} observations would enable us to distinguish between (1) a genuinely narrow-line radio galaxy that is obscured by a Compton-thick absorber (in which case the <10 keV X-ray continuum would show few, if any, signs of heavily absorbed emission), and (2) a low-excitation radio galaxy with a prominent extended emission-line environment. We will return to this point in subsequent publications (M. Birkinshaw et al. 2008, in preparation; M. J. Hardcastle et al. 2008, in preparation).

7. CONCLUSIONS

We have presented results from XMM-Newton observations of the nuclei of the radio galaxies 3C 305, DA 240, and 4C 73.08. We have shown the following:

1. The X-ray spectrum of the narrow-line FR II radio galaxy 4C 73.08 can be modeled as the sum of a heavily absorbed power law associated with a luminous accretion disk and circumnuclear obscuring structure, together with an unabsorbed component of X-ray emission that has a common origin with the radio emission at the base of an unresolved jet. This behavior is consistent with the other narrow-line FR II radio galaxies studied by Evans et al. (2006) and Hardcastle et al. (2006).

2. The nuclear X-ray spectrum of the FR II giant radio galaxy DA 240, optically classified as a low-excitation radio galaxy, can be modeled as a single, unabsorbed power law that is likely associated with emission from the parsec-scale jet. The upper limit to the X-ray luminosity of any additional, accretion-related emission suggests that the accretion process in DA 240 is substantially sub-Eddington and likely radiatively inefficient in nature.

3. The X-ray emission in the nucleus of the narrow-line radio galaxy 3C 305 can be modeled as an unabsorbed power law that originates at the base of the jet. However, it shows no evidence for heavily absorbed X-ray emission was found in the NLRGs studied by Evans et al. (2006).

4. We have discovered an X-ray counterpart to the northeast hot spot of the giant radio galaxy DA 240. We argue that the emission process is overwhelmingly likely to be synchrotron emission. Because of the high X-ray flux of the hot spot, it is a good candidate for follow-up high-resolution X-ray observations.

5. We have discussed the different origins of optical emission lines in the nuclear and circumnuclear gaseous environments of radio galaxies. These include photoionization from the AGN accretion flow or parsec-scale jet, shock excitation by the radio jet, or cooling gas in the centers of clusters. This may lead to occasional misclassification of genuinely weak-lined sources such as 3C 305 as high-excitation sources.

6. We therefore argue that there is not necessarily always a one-to-one correspondence between optical emission-line class (low vs. high excitation) and accretion-flow state (inefficient flow vs. standard thin disk), especially when low angular resolution optical spectroscopy is used. We suggest that only the combination of high-resolution optical, X-ray, and infrared observations
can reliably uncover the nature of the central engine in radio-
loud AGNs.

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