THE NUCLEI OF RADIO GALAXIES IN THE ULTRAVIOLET: THE SIGNATURE OF DIFFERENT EMISSION PROCESSES

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ABSTRACT

We have studied the nuclei of 28 radio galaxies from the 3CR sample in the UV band. Unresolved nuclei (central compact cores: CCCs) are observed in 10 of the 13 FR I galaxies, and in five of the 15 FR II galaxies. All sources that do not have a CCC in the optical do not have a CCC in the UV. Two FR I galaxies (3C 270 and 3C 296) have a CCC in the optical but do not show the UV counterpart. Both of them show large dusty disks observed almost edge-on, possibly implying that they play a role in obscuring the nuclear emission. We have measured optical-UV spectral indices \( \alpha_{\text{opt}, \text{UV}} \) between \(-0.6\) and \(-7.0\) \( (F_{\nu} \propto \nu^{-\alpha}) \). Broad-line radio galaxies have the flattest spectra, and their values of \( \alpha_{\text{opt}, \text{UV}} \) are also confined to a very narrow range. This is consistent with radiation produced in a geometrically thin, optically thick accretion disk. On the other hand, FR I nuclei, which are most plausibly originated by synchrotron emission from the inner relativistic jet, show a wide range of \( \alpha_{\text{opt}, \text{UV}} \). There is a clear trend with orientation in that sources observed almost edge-on or with clear signs of dust absorption have the steepest spectra. These observations imply that in FR I galaxies, obscuration can be present, but the obscuring material is not in a "standard" geometrically thick torus. The most striking difference between these absorbing structures and the classic active galactic nucleus "tori" resides in the lower optical depth of the FR I galaxy obscuring material.

Subject headings: galaxies: active — galaxies: nuclei — radiation mechanisms: general — ultraviolet: galaxies

1. INTRODUCTION

In the framework of the unification models for radio-loud active galactic nuclei (AGNs), radio galaxies are believed to be the misoriented counterparts of quasars and blazars (Barthel 1989; for a review, see Urry & Padovani 1995). Although observationally this scheme is mainly supported by the comparison of the extended components of these classes of AGNs, a direct study of their nuclear properties is a crucial tool both for confirming such a framework and for inferring fundamental information about the innermost structure of these sources.

In quasars and blazars, the nuclear components dominate the observed radiation. Their origin is generally believed to reside in thermal emission from the accretion disk and nonthermal emission from the relativistic jet, respectively. In the case of blazars, the jet is observed almost along its axis, and its emission is strongly enhanced by relativistic beaming (Antonucci & Ulvestad 1985). In radio galaxies, all these components should still be present, although the presence of obscuring structures in the inner few parsecs, which is strictly required by the unification models, at least in the case of the most powerful sources (FR II galaxies), might hamper their direct observation. Moreover, the inner jet emission should be strongly deamplified in radio galaxies, due to the much larger angle of the line of sight–to–jet direction.

The detection of faint nuclear optical components (central compact cores [CCCs] or "nuclei") in 3CR radio galaxies, which are still unresolved even in Hubble Space Telescope (HST) images (Chiaberge, Capetti, & Celotti 1999, hereafter Paper I), allows us to directly investigate the properties of the optical emission from the active nucleus in this class of sources.

The picture that emerges from these studies is that nearby radio galaxy nuclei have two main flavors. A large fraction of FR II galaxies appear to be consistent with the currently accepted scheme: they either show strong optical nuclei associated with narrow and broad emission lines or absorbed nuclei (either not detected or seen through scattered light) in objects with only narrow emission lines (Chiaberge, Capetti, & Celotti 2000a, hereafter Paper II; 2002). On the other hand, most FR I galaxies have unobscured synchrotron-dominated optical nuclei and low-efficiency radiating accretion disks (e.g., advection-dominated accretion flows; Rees et al. 1982; Narayan & Yi 1995) and lack substantial emission-line regions. Surprisingly, a significant fraction of FR II galaxies in which broad lines are not detected show faint optical nuclei with optical-radio properties indistinguishable from those of FR I galaxies. The
nature of these sources is still unclear, although their consistency with the FR I nuclei suggests that at least some of them might be unobscured synchrotron nuclei as well. These results have found support in the recent observations by Whysong & Antonucci (2001) of a strong 10 μm nuclear thermal component in Cyg A (3C 405, an FR II galaxy), which is not observed in M87 (3C 274, an optically unobscured FR I galaxy; see also Perlman et al. 2001).

In light of these results, a classification of radio galaxies based on their nuclear properties seems to be more closely related to the physical process occurring in the central regions of the sources rather than in the old FR I/FR II galaxy morphological dichotomy. This appears to be (at least qualitatively) consistent with the dual-population scheme proposed recently (Jackson & Wall 1999), which unifies the different sources mainly on the basis of their spectral properties.

However, due to the lack of complete spectral information on the nuclei, several questions are still waiting for a definitive answer: Are FR I and FR II nuclei intrinsically different? What is the role of obscuration in FR I galaxies? What is the role of the different “flavors” of radio galaxies in the AGN paradigm?

In this paper, we test the nature of radio galaxy nuclei, using HST/STIS UV observations. High-resolution UV data are crucial in order to test the new picture of the radio galaxy dichotomy. In view of the relatively low intensity of the underlying stellar emission from the host galaxy, the detection of CCCs in UV images is straightforward. Due to the reasonably large difference in frequency between UV and optical data, we can derive the spectral shape in this critical region, where different spectral properties are expected for different origins of the observed nuclear components. Furthermore, UV emission is very sensitive to obscuration by dust; therefore, the presence of even moderate amount of absorption along the line of sight to the nuclei will clearly affect their observed spectral properties.

The paper is organized as follows: in §2 we describe the sample and the HST observations. In §3 we outline our method for the detection and photometry of the nuclei in the UV images and compare it with what has been done in the optical. In §4 we show our results, and we combine them with the available radio and optical nuclear data, while in §5 we discuss the implications of our results for the nuclear structure and the origin of the emission. In §6 we present a summary of our findings and we draw conclusions.

2. THE SAMPLE AND THE HST OBSERVATIONS

We analyze a sample of nearby (z < 0.1) FR I and FR II radio galaxies belonging to the 3CR catalog, for which both optical and UV HST observations are available. The sample comprises 28 radio galaxies, 13 of them morphologically classified as FR I galaxies and 15 as FR II galaxies. Of the 15 FR II galaxies, seven are HEGs (high-excitation galaxies), five are LEGs (low-excitation galaxies; Hine & Longair 1979; Jackson & Rawlings 1997), and three are broad-line radio galaxies (BLRGs). The list of the sources is shown in Table 1.

All objects, except for 3C 78, 3C 264, and M87, have been observed with the HST as part of the STIS UV snapshot survey of 3CR radio sources (Allen et al. 2002). We have excluded from the sample 3C 231 (M82), which is a starburst galaxy, STIS observations have been made with the NUV-MAMA detector and filters with peak sensitivity at ~2300 Å. In particular, most of the images were obtained with the F25SRF2 long-pass filter, which excludes strong contamination from the Lyα emission line within the redshift range of our sources. The brightest objects have been observed with the narrower band F25CN182 filter in order to avoid saturation. M87 and 3C 78 have also been observed by the STIS NUV-MAMA, using the F25QTZ filter (whose characteristics are similar to F25SRF2), while 3C 264 has been observed using the F25CN182 filter.

The log of optical and UV observations is presented in Table 2, in which it can be seen that for four sources (M87, 3C 78, 3C 264, and 3C 317), the observations occurred simultaneously (or nearly simultaneously). Given that all sources in the sample are likely to be intrinsically variable, the time lapse between observations of the other 24 sources might be significant, and we discuss this point further in §5.3.

The sample is not statistically complete, because a few sources were not observed during the SNAPSHOT campaign. However, all the different spectral and morphological types present in 3CR radio galaxies with z < 0.1 are well represented.

3. DETECTION AND PHOTOMETRY OF UV CCCs

As shown in detail by Allen et al. (2002), the morphology of radio galaxies as observed in the UV band can be significantly different from what is seen in the optical images. This certainly holds in the nuclear region, where dust features dramatically absorb the underlying emission in the UV and clumps of (likely) star formation are present. Also, in that band the stellar emission from the host galaxy is substantially reduced with respect to optical (R-band) frequencies, typically by a factor of ~15, in an F3 representation.

Most of the UV images have a very low level of stellar emission. Therefore, while the search for optical CCCs has been based on the analysis of the surface brightness profiles of the central regions of the galaxies (Paper I; Paper II), here we search directly for the UV counterparts of the optical CCCs. In addition, we also search for unresolved UV CCCs in galaxies that do not have optical CCCs, but find none. All of the UV CCC sources have FWHM ~0.05–0.07, indicating that they are unresolved by HST.

Of the 13 FR I galaxies in our sample, 10 (or 77% of the sample) have a UV nucleus. In the optical, 12 (92%) have a CCC. Whenever a galaxy has a nucleus in the UV, it also has a nucleus in the optical. Of all the FR I galaxies in the sample, only 3C 305 does not have a CCC either in the optical or in the UV. Interestingly, the two sources that lack the UV CCC but do have it in the optical (namely, 3C 270 and 3C 296) have prominent nuclear dusty disks observed almost edge-on (Capetti & Celotti 1999; Martel et al. 2000). These disks are clearly visible in both the optical and the UV images.

Of the 15 FR II galaxies of our sample, only five sources have a nucleus in the UV. All of them also have a CCC in the optical. In particular, a CCC is present in all three of the BLRGs, and only in ⅓ and ⅔ of the HEGs and LEGs, respectively. The BLRGs have the brightest nuclei of the sample.

4 3C 78 and 3C 264 have been observed with STIS as part of program 8233, while M87 has been observed as part of program 8140 (PI J. Biretta).
TABLE 1
THE SAMPLE

| Name          | Morphological Classification | Spectral Classification | Redshift | $F_\text{r}$ (mJy) | Optical CCC | UV CCC |
|---------------|-------------------------------|-------------------------|----------|--------------------|-------------|-------|
| 3C 29         | FR I                          |                         | 0.0448   | 93.0               | YES         | YES   |
| 3C 35         | FR II                         | LEG                     | 0.0670   | 22.68              | NO          | NO    |
| 3C 40         | FR II                         | LEG                     | 0.0180   | 626.9              | NO          | NO    |
| 3C 78         | FR I                          |                         | 0.29     | 964                | YES         | YES   |
| 3C 66B        | FR I                          |                         | 0.215    | 182.0              | YES         | YES   |
| 3C 192        | FR II                         | LEG                     | 0.0500   | 8.1                | NO          | NO    |
| 3C 198        | FR III                        | HEG                     | 0.0970   | 252.4              | YES         | YES   |
| 3C 227        | FR II                         | BURG                    | 0.0670   | 23.23              | YES         | YES   |
| 3C 236        | FR II                         | LEG                     | 0.0990   | 12.0               | NO          | NO    |
| 3C 264        | FR I                          |                         | 0.0227   | 200.0              | YES         | YES   |
| 3C 270        | FR I                          |                         | 0.0074   | 308.0              | NO          | NO    |
| 3C 274 (M87)  | FR I                          |                         | 0.0037   | 4000.0             | YES         | YES   |
| 3C 285        | FR III                        | HEG                     | 0.0452   | 100.0              | NO          | NO    |
| 3C 293        | FR II                         | LEG                     | 0.0327   | 77.0               | YES         | YES   |
| 3C 305        | FR I                          |                         | 0.0810   | 23.5               | NO          | NO    |
| 3C 310        | FR I                          |                         | 0.0640   | 80.0               | YES         | YES   |
| 3C 317        | FR I                          |                         | 0.0342   | 391.0              | YES         | YES   |
| 3C 321        | FR II                         | HEG                     | 0.0960   | 37.5               | NO          | NO    |
| 3C 326        | FR II                         | LEG                     | 0.0890   | 15.7               | NO          | NO    |
| 3C 338        | FR I                          |                         | 0.0303   | 105.0              | YES         | YES   |
| 3C 353        | FR II                         | LEG                     | 0.0300   | 203.5              | NO          | NO    |
| 3C 382        | FR II                         | BURG                    | 0.0580   | 217.4              | YES         | YES   |
| 3C 388        | FR II                         | LEG                     | 0.0390   | 75.67              | YES         | YES   |
| 3C 390.3      | FR III                        | BURG                    | 0.0560   | 414                | YES         | YES   |
| 3C 449        | FR I                          |                         | 0.0181   | 37.0               | YES         | YES   |
| 3C 452        | FR II                         | HEG                     | 0.0810   | 150                | NO          | NO    |
| 3C 465        | FR I                          |                         | 0.0301   | 270.0              | YES         | YES   |

Note.—Classifications and data from the literature for the sample of 3CR radio galaxies. Col. (1): 3C name of the source. Col. (2): Radio morphological classification. Col. (3): Optical spectral classification, as taken from Jackson & Rawlings 1997. Col. (4): Redshift (from NED). Col. (5): Radio core flux at 5 GHz collected from the literature (Giovannini et al. 1988; Zirbel & Baum 1995). Cols. (6) and (7): Presence/absence of a CCC in the HST images (Paper I, Paper II; Allen et al. 2002; and this work).

$HST$ data are available for 3C 285 both in the $R$ and $V$ bands. A faint CCC is present in the $R$-band image, but this component is not detected in the $V$-band. In this case, obscuration might be provided by a prominent large-scale dust lane, similar to that observed in Cen A. In this latter object, the IR-bright nucleus vanishes in $HST$ images for wavelengths shorter than $\sim 5000$ Å (Marconi et al. 2000).

We have performed aperture photometry of all the nuclei using the IRAF RADPROF task, setting the background level at a distance of $\sim 0.17$ (7 pixels in the STIS/MAMA images) from the center. Counts were converted to fluxes adopting the $HST$ internal calibration, which is accurate to 5%. However, except for those sources in which the CCC is clearly the only observed component in the UV, the dominant source of error is the presence of some extended emission from the host galaxy and/or absorption features that might strongly affect the background determination. This results in a typical error of $\sim 10\%$, therefore comparable to that in the optical.

For 3C 270, we derive a rough upper limit to the nuclear flux, as the presence of a dusty disk and emission features in both the optical and UV images allows us to identify the position of the nucleus, although it is not visible in the UV. For the remaining objects, no reliable upper limits can be derived. Also note that the LEG 3C 35 has a UV central component that is not a point source.

4. RESULTS

The results of the photometry of the CCCs are summarized in Table 3. For completeness, we also include the optical fluxes, as taken from Papers I and II. Since in the UV band dust absorption plays an important role in drastically reducing the observed flux, we have reddened the fluxes taking into account the galactic absorption and adopting the Cardelli, Clayton, & Mathis (1988) extinction law (Table 4). In the following sections and figures, we use the reddened fluxes, although galactic extinction does not significantly affect the results in any of the sources.

5 The PHOTFLAM parameter in the image header (inverse sensitivity) is defined assuming a flat spectral distribution in $F_\lambda$ (in units of $\text{ergs cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$). As we show in the following, most of the nuclei have significantly sloped spectral indices. We have therefore recalculated the effective observing wavelength and the value of the inverse sensitivity with an iterative process for all of the sources, using the SYNPHOT package. Only in the case of 3C 449, the source with the steepest observed spectrum, does this significantly affect the effective observing wavelength and the estimate of the flux.

6 The maximum value of the color excess due to galactic absorption is $E(B-V) = 0.167$ in the case of 3C 449. This value of $E(B-V)$ affects the UV and optical fluxes by factors of only 3 and 1.4, respectively.
To study the relationship between the optical and UV CCCs for the 15 sources of Table 4, we plot their UV flux and luminosity versus their optical values. The same behavior is observed in both the flux and luminosity regimes: we see that the UV CCCs span a range of ~5 dex in flux and ~6 dex in luminosity, whereas the optical CCCs span smaller ranges (about 1 dex in both flux and luminosity).

Given the large difference in frequency between the optical (R-band) and UV observations, we could derive the broadband spectral indices (optical-UV) with consid-

### TABLE 2

Log of HST Optical and UV Observations

| Name       | Instrument | Filter | Observation Date | Instrument | Filter | Observation Date |
|------------|------------|--------|------------------|------------|--------|------------------|
| 3C 29....... | WFPC2      | F702W  | 1995 Jan 12      | STIS NUV-MAMA | F25SRF2 | 2000 Jun 8       |
| 3C 35....... | WFPC2      | F702W  | 1994 Mar 12      | STIS NUV-MAMA | F25SRF2 | 1999 Oct 10      |
| 3C 40....... | WFPC2      | F702W  | 1994 Jul 18      | STIS NUV-MAMA | F25SRF2 | 2000 Jun 6       |
| 3C 66B...... | WFPC2      | F814W  | 1999 Jan 31      | STIS NUV-MAMA | F25SRF2 | 2000 Jul 13      |
| 3C 78....... | STIS CCD   | F28X50LP | 2000 Mar 15    | STIS NUV-MAMA | F25QTZ | 2000 Mar 15      |
| 3C 192..... | WFPC2      | F555W  | 1997 Jan 13      | STIS NUV-MAMA | F25SRF2 | 2000 Mar 23      |
| 3C 198..... | WFPC2      | F702W  | 1994 Mar 20      | STIS NUV-MAMA | F25SRF2 | 2000 Apr 23      |
| 3C 227..... | WFPC2      | F702W  | 1995 May 19      | STIS NUV-MAMA | F25SRF2 | 2000 Jun 25      |
| 3C 236..... | WFPC2      | F702W  | 1994 Oct 19      | STIS NUV-MAMA | F25SRF2 | 1999 Oct 5       |
| 3C 264..... | STIS CCD   | F28X50LP | 2000 Feb 13   | STIS NUV-MAMA | F25CN182 | 2000 Feb 12  |
| 3C 305..... | FOC        | F555W  | 1994 Mar 5       | FOC        | F210M   | 1994 Mar 5       |
| 3C 306..... | WFPC2      | F702W  | 1994 Apr 29      | STIS NUV-MAMA | F25SRF2 | 2000 Mar 12      |
| 3C 338..... | WFPC2      | F702W  | 1994 Sep 9       | STIS NUV-MAMA | F25SRF2 | 2000 Jun 4       |
| 3C 353..... | WFPC2      | F702W  | 1995 Mar 18      | STIS NUV-MAMA | F25SRF2 | 2000 Jun 22      |
| 3C 382..... | WFPC2      | F702W  | 1994 Jun 25      | STIS NUV-MAMA | F25CN182 | 2000 Feb 23    |
| 3C 388..... | WFPC2      | F702W  | 1994 Sep 18      | STIS NUV-MAMA | F25SRF2 | 2000 Jun 2       |
| 3C 390..... | WFPC2      | F702W  | 1994 Sep 20      | STIS NUV-MAMA | F25CN182 | 1999 Aug 10  |
| 3C 449..... | WFPC2      | F702W  | 1994 Aug 6       | STIS NUV-MAMA | F25SRF2 | 2000 Apr 16      |
| 3C 452..... | WFPC2      | F702W  | 1994 May 5       | STIS NUV-MAMA | F25SRF2 | 2000 Jan 30      |
| 3C 465..... | WFPC2      | F814W  | 2000 Jul 3       | STIS NUV-MAMA | F25SRF2 | 2000 May 25      |

### TABLE 3

Observed Fluxes of Optical and UV CCCs

| Source Name | $F_o$ (ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$) | $\lambda_o$ (Å) | $F_{UV}$ (ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$) | $\lambda_{UV}$ (Å) |
|-------------|----------------------------------------|----------------|---------------------------------------------|-------------------|
| **FR I**    |                                        |                |                                             |                   |
| 3C 29........ | $5.8 \times 10^{-18}$                  | 7000           | $2.1 \times 10^{-19}$                       | 2528              |
| 3C 66B....... | $2.7 \times 10^{-17}$                  | 8086           | $4.5 \times 10^{-17}$                       | 2528              |
| 3C 382....... | $3.8 \times 10^{-16}$                  | 7216           | $2.8 \times 10^{-16}$                       | 2475              |
| 3C 388....... | $1.6 \times 10^{-16}$                  | 7216           | $3.0 \times 10^{-16}$                       | 2078              |
| 3C 390....... | $5.1 \times 10^{-18}$                  | 7930           | $<1.0 \times 10^{-18}$                      | 2528              |
| 3C 449....... | $3.4 \times 10^{-16}$                  | 8086           | $3.8 \times 10^{-16}$                       | 2475              |
| 3C 465....... | $3.5 \times 10^{-18}$                  | 7000           | $1.6 \times 10^{-18}$                       | 2528              |
| 3C 270a....... | $2.0 \times 10^{-17}$                  | 5508           | $4.7 \times 10^{-17}$                       | 2213              |
| 3C 310....... | $1.0 \times 10^{-17}$                  | 7000           | $3.9 \times 10^{-18}$                       | 2528              |
| 3C 317....... | $2.0 \times 10^{-17}$                  | 7000           | $1.9 \times 10^{-19}$                       | 3256              |
| 3C 338....... | $1.0 \times 10^{-17}$                  | 8086           | $2.1 \times 10^{-18}$                       | 2528              |
| **FR II**   |                                        |                |                                             |                   |
| 3C 198....... | $4.9 \times 10^{-17}$                  | 7000           | $1.1 \times 10^{-16}$                       | 2528              |
| 3C 227....... | $2.9 \times 10^{-16}$                  | 7000           | $5.9 \times 10^{-16}$                       | 2528              |
| 3C 388....... | $6.7 \times 10^{-18}$                  | 7000           | $2.0 \times 10^{-18}$                       | 2528              |
| 3C 390.3..... | $1.1 \times 10^{-15}$                  | 7000           | $2.0 \times 10^{-15}$                       | 2078              |

* For 3C 270, an upper limit to the UV CCC has been derived (see § 3).
erably greater accuracy than previously possible (Paper I). The values of $\alpha_{\text{opt}}$, where $\alpha$ is defined as $F_{\alpha} \propto \nu^{-\alpha}$, are reported in Table 4. Typical errors for $\alpha$ are of the order of $\pm 0.1$. For reference, in Figures 1 and 2 we have overplotted dashed lines corresponding to different optical-UV spectral indices $\alpha_{\text{opt}} = 1, 2, 4, \text{ and } 6$ (top to bottom). We find that the UV and optical luminosities of the brightest sources are almost identical. However, the lower optical luminosity sources have much weaker UV emission (by a factor of $\sim 100$).

In Figure 3 we plot the optical-UV spectral index versus the ratio of the optical CCC to the radio core flux. The quasi linearity of the FR I galaxy radio-optical correlation implies a quasi-constant ratio of the optical-to-radio flux [corresponding to $\log(F_{\text{opt}}/F_{\text{r}}) \sim -3.6$]; therefore, objects on the left side of this plot are on the FR I galaxy correlation,

TABLE 4
Derredened UV and Optical Data of the CCCs

| Source Name | Spectral Classification (2) | $\log F_{\text{o}}$ (ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$) | $\log F_{\text{UV}}$ (ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$) | $\log L_{\text{o}}$ (ergs s$^{-1}$ Hz$^{-1}$) | $\log L_{\text{UV}}$ (ergs s$^{-1}$ Hz$^{-1}$) | $\alpha_{\text{opt}}$ | $\sigma_{\alpha}$ | $E(B-V)$ |
|-------------|--------------------------|-----------------|-----------------|-----------------|-----------------|-------------|-------------|-----------|
| 3C 29............| ...| -27.99| -30.25| 26.57| 24.31| 5.1| 0.2| 0.036|
| 3C 66B............| ...| -27.18| -27.80| 26.76| 26.13| 1.2| 0.1| 0.080|
| 3C 78............| ...| -26.03| -26.74| 28.15| 27.44| 1.5| 0.1| 0.173|
| 3C 264............| ...| -26.54| -27.28| 27.36| 26.61| 1.4| 0.1| 0.023|
| 3C 270............| ...| -27.96| -29.62| 25.05| 23.39| >3.4| ...| 0.018|
| 3C 274............| ...| -26.12| -27.05| 26.30| 25.37| 1.8| 0.1| 0.022|
| 3C 310............| ...| -28.21| -29.35| 25.50| 25.36| 2.6| 0.1| 0.042|
| 3C 317............| ...| -27.65| -28.97| 26.68| 25.35| 3.3| 0.2| 0.037|
| 3C 338............| ...| -27.78| -29.05| 26.44| 25.17| 2.9| 0.1| 0.012|
| 3C 449............| ...| -27.38| -29.83| 26.40| 23.95| 7.3| 0.2| 0.167|
| 3C 465............| ...| -27.61| -29.16| 26.60| 25.06| 3.1| 0.1| 0.069|
| 3C 198.............| HEG| -27.08| -27.56| 27.98| 27.50| 1.1| 0.1| 0.026|
| 3C 227.............| BLRG| -26.30| -26.83| 28.79| 28.26| 1.2| 0.1| 0.026|
| 3C 382.............| BLRG| -25.03| -25.37| 29.74| 29.40| 0.6| 0.1| 0.070|
| 3C 388.............| LEG| -27.89| -29.15| 27.25| 25.99| 2.8| 0.2| 0.080|
| 3C 390.3..........| BLRG| -25.68| -26.27| 29.06| 28.47| 1.1| 0.1| 0.071|

Note.—Fluxes and luminosities dereddened taking into account galactic absorption (col. [8] is from the NED).

FIG. 1.—UV flux vs. optical flux of the CCCs. Filled circles represent FR I galaxies, while FR II galaxies are represented by open circles. The dashed lines represent values of $\alpha_{\text{opt}} = 1, 2, 4, \text{ and } 6$ (top to bottom).

FIG. 2.—UV vs. optical luminosity of the CCCs. Filled circles represent FR I galaxies, while FR II galaxies are represented by open circles. The dashed lines represent values of $\alpha_{\text{opt}} = 1, 2, 4, \text{ and } 6$ (top to bottom).
while for higher values of \( \log(F_o/F_r) \), an optical excess is present. The shaded area corresponds to the rms of the correlation (see figure caption for details). Unfortunately, no radio core measurements are available in the literature for 3C 198; therefore, its position is this plane is undetermined. Sources clearly separate in this plane. Broad-line FR II galaxies have a similar (and rather flat) \( \alpha_{o,UV} \). The synchrotron-dominated FR I galaxies have lower values of \( F_o/F_r \) by a factor of \( \sim 10-100 \); they lie in the region of the correlation between the radio and optical cores, but span a large range in \( \alpha_{o,UV} \). Interestingly, the only LEG FR II galaxy with a detected CCC (3C 388) lies in the region typical of FR I galaxies. For comparison, we have also plotted radio-loud quasars\(^7\) with \( z < 0.3 \) from the sample of Elvis et al. (1994).

Since these sources are at a higher redshift than our 3C galaxies, we have used the \( J \)-band magnitudes and the UV fluxes measured at 3000 \( \AA \) (as taken from Elvis et al. 1994) to mimic the rest-frame \( \alpha_{o,UV} \). BLRGs in our sample and the quasars occupy the same region of the plane, except for 3C 273. In the following, we discuss the implications of the different position of the sources in this plane, strongly supporting a different origin of the nuclear emission in the various classes of radio galaxies.

5. DISCUSSION

UV data are a fundamental tool for studying the effects of obscuration in the central regions of these galaxies, as this spectral band is very sensitive to the presence of dusty structures. Also, different emission processes for the nuclei imply different values of the optical-UV spectral slopes. By combining the UV data with the already available radio and optical data, we can address some important questions, such as the following:

1. Are FR I and FR II galaxies intrinsically different?
2. What do the UV observations tell us about their physical nature?
3. What is the role of these sources in the AGN paradigm?
4. What is the role of obscuration in FR I galaxies?

Qualitatively, FR II nuclei are brighter and have flatter spectral slopes than FR I nuclei. Such a behavior can be accounted for by two basic scenarios: (1) an intrinsic spectral difference, reflecting different physical properties, and (2) an external reason, namely, a different amount of absorption in the various sources. Obviously, it is also possible that a combination of these two factors contributes to defining the observed properties. Whatever the nature of the CCCs, an increasing column density naturally both steepens the spectral slope and lowers the amount of observed photons. However, the physical processes responsible for the emission cannot be constrained on the basis of only the optical and UV fluxes and luminosities.

In the following sections we further discuss the nature of the CCCs by taking advantage of the already known behavior of the different sources in the radio-optical plane.

5.1. Disk-dominated versus Synchrotron-dominated Sources

It is widely believed that in radio-loud AGNs, two main emitting components play a role in defining the optical-UV spectral properties of the nuclear continuum: the thermal emission from the accretion disk and the nonthermal synchrotron radiation from the relativistic jet. In addition, we must consider the role of absorption, which might significantly alter the observed spectra. Theoretical models for thermal disk emission (in the case of a standard Shakura-Sunyaev optically thick and geometrically thin disk) predict that such a component should peak in the UV band, at wavelengths shorter than 1000 \( \AA \); therefore, hard UV spectral slopes \( \alpha_{o,UV} \sim 0.3 \) are expected. Flat spectral components with \( \alpha_{o,UV} < 1 \) are indeed commonly observed in both radio-quiet and radio-loud quasars (see, e.g., Elvis et al. 1994).

On the other hand, the spectral slope of synchrotron-dominated sources is poorly constrained, as it depends on physical parameters (mainly on the electron distribution, the magnetic field, and the beaming factor) that cannot be easily determined a priori. However, we can try to estimate it by analogy with other synchrotron-emitting sources for which the spectral energy distribution (SED) is well known. In the framework of the AGN unification schemes, radio galaxies are believed to constitute the so-called parent population of blazars; therefore, the comparison with the observed properties of these sources might be helpful. Blazars are objects in which the jet is believed to be observed almost “on-axis.” Their observed SED [in a log \( v \)-log(\( F_v \)) representation] is composed of two broad peaks: the lower energy peak is commonly interpreted as being due to synchrotron emission, while the high-energy peak is ascribed to inverse Compton emission. The frequency of the peaks can vary substantially from one source to another: the lower

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\(^7\) The radio-loud quasars with \( z < 0.3 \) from the Elvis et al. (1994) sample are 3C 206 (\( z = 0.197 \)), 3C 323.1 (\( z = 0.264 \)), MC2 1635+119 (\( z = 0.146 \)), PHL 1657 (\( z = 0.2 \)) PG 0007+106 (\( z = 0.089 \)), B2 1028+313 (\( z = 0.178 \)), 3C 273 (\( z = 0.158 \)), and 4C 34.47 (\( z = 0.206 \)).
energy peak can be located between the IR and the X-ray band, while the higher energy peak is generally in the gamma-ray band. Fossati et al. (1998) have shown that the position of the synchrotron peak, which is well constrained by the observations, is related to the bolometric luminosity of the source. The lower the power of the object, the higher the synchrotron peak frequency $\nu_{\text{peak}}$.

Clearly, the relative position of the peak and the observing frequencies strongly affects the observed UV-optical spectral index. For objects in which $\nu_{\text{peak}}$ is significantly lower than the observing range, steep ($\alpha \sim 1-3$) spectral indices are measured, while flatter spectra ($\alpha \sim 0.5-1$) are observed if $\nu_{\text{peak}}$ is placed at higher frequencies.

Relativistic effects must also be taken into consideration in order to estimate the putative position of the synchrotron peak for our nuclei. Since the emission from the jet is strongly affected by beaming, the peak frequency shifts toward lower values and (most importantly) toward lower luminosities as the angle between the jet axis and the line of sight increases. However, as a result of beaming, it is possible that in highly misoriented objects such as most radio galaxies, the radiation emitted by a slower component of the jet (e.g., a layer) might dominate the observed emission, while the (faster) component that dominates blazar emission might not be observed (Chiaberge et al. 2000b).

Unfortunately, the spectral properties of this component are still very poorly known.

The positions of the objects in the plane formed by the optical-UV spectral index versus the logarithm of the ratio of optical CCC flux to radio core flux, which is shown in Figure 3 and has been described in § 4, can be interpreted as being related to the different nature of their nuclear emission. Objects in our sample that show an optical excess with respect to the radio-optical correlation are BLRG FR II galaxies and have flatter spectral indices ($\alpha_{\text{opt,UV}} \sim 0.6-1.2$). These sources occupy the same region of the plane as radio-loud quasars of comparable redshift, from the Elvis et al. (1994) sample, which are plotted as stars. The SED of the quasars is well known, and it clearly shows the presence of a "blue bump," which is commonly interpreted as the most prominent signature of thermal emission from the accretion disk. The only quasar with a lower value of $\log(F_o/F_r)$ is 3C 273, which is classified as a blazar. The contribution from the relativistic jet emission (which generally shows strong variations) in this spectral region can indeed substantially alter the observed spectrum in this source (Ghisellini et al. 1998). In fact, it lies close to the region of the FR I galaxy correlation, indicating that thermal disk emission is low in the optical band but shows a flat $\alpha_{\text{opt,UV}} < 1$, implying the presence of a strong component at higher energies, similar to what is observed in other quasars.

We conclude that our BLRGs are compatible with being thermal disk–dominated objects. Their distance from the shaded region is possibly determined by the relative contribution of the disk and jet emission, which might also be related to the source orientation.

As pointed out above, FR I galaxies show a different behavior. They have similar values of $F_o/F_r$, since they lie on the radio-optical correlation, while they span a large range in $\alpha_{\text{opt,UV}}$, from $\sim 1$ to the extreme case of 3C 449, for which $\alpha_{\text{opt,UV}} = 7$. However, taking into account the above considerations, we can conclude that slopes significantly flatter or steeper than unity are not expected for our sources. Steep spectral slopes in synchrotron spectral components can be observed only for a relatively small range of frequencies, which is confined to be well above the low-energy peak, but still before the rising of the inverse Compton component. Therefore, intrinsic values of $\alpha_{\text{opt,UV}}$ larger than $\sim 3$ appear to be implausible for synchrotron-emitting sources. In the following section, we show that a moderate amount of absorption can account for the observed behavior.

5.2. Evidence for a Moderate Amount of Obscuration in FR I Galaxies

The apparent inconsistency between the synchrotron scenario and the presence of such steep spectral slopes can be solved if a modest amount of absorption is present, since it might naturally contribute to steepening the observed spectrum. In order to test whether the range of spectral indices and their relative amounts of radio, optical, and UV emission is compatible with being due to absorption, we have plotted in Figure 4 the ratio of radio-to-UV emission versus the ratio of optical-to-UV emission. The dashed line is the "absorption trail," which has been calculated by taking into account the effects of an increasing amount of absorption on the observed optical and UV fluxes.

All FR I galaxies (except for 3C 449) are well aligned to such a line. The FR II galaxy 3C 388 lies on the absorption trail as well. If we assume an intrinsic slope of 1 for all these sources, the range of observed $\alpha_{\text{opt,UV}}$ corresponds to a very small amount of absorption. A maximum $A_V$ of $\sim 6$ is obtained in the extreme case of 3C 449, while all other sources are between 0.15 and 3 (the median being $A_V = 1.3$). Although this is clear evidence of nuclear absorption in FR I sources, these observations show that the properties of the absorbing material are not compatible with a standard geometrically thick torus structure. In fact, the position of the
sources along the absorption trail in Figure 4 is strictly connected with orientation. On the one hand, the sources that appear to be the less absorbed (namely, 3C 264, 3C 66B, 3C 78, and 3C 274, lying on the bottom left of the plane close to the BLRGs) are all objects in which optical jets are seen. The presence of such features has been interpreted as being due to their relatively small viewing angle (Sparks et al. 2000), which, as a result of relativistic beaming, contributes to enhancing the jet radiation. On the other hand, dusty disks observed almost edge-on are seen among the most absorbed sources (e.g., 3C 449 and 3C 465; Capetti & Celotti 1999; Martel et al. 2000). In the most extreme cases (3C 270 and 3C 296), the nuclear source is clearly visible in the optical, but it is not present in the UV. Such a trend with orientation implies that the absorbing material cannot be distributed as either a spherical structure (all sources should be affected by absorption) or a thin disk where the absorbing material is well confined. In the latter case, in fact, no trend with orientation should be seen: sources should be either absorbed or not absorbed without any intermediate case. However, the most striking difference between these structures and the classic AGN “tori” resides in the lower optical depth of the FR I absorbers, which allow us to observe the CCC even in the UV in all FR I galaxies, except for the most extreme cases of 3C 270 and 3C 296.

In light of these results, we can confirm the claim that FR I nuclei are generally unabsorbed. The moderate amount of absorption observed in these objects cannot be ascribed to the presence of a “classic” torus-like structure that is typical of other AGNs and might instead be accounted for either by extended (kiloparsec-scale) dust lanes (e.g., in the case of 3C 29, in which the signature of a dust lane is clearly visible in the HST images; Sparks et al. 2000) or by the (~100 pc scale) dusty disks. In the latter case, the absorbing column density must vary smoothly for different viewing angles.

As already noted above, one FR II galaxy (3C 388, which is classified as an LEG) lies in the region typical of FR I galaxies. This appears to confirm what has already been found in Paper II: 3C 388 belongs to a third class of FR II sources whose optical nuclei are indistinguishable from those of FR I galaxies (we have called such a class “FR I-like”). The fact that this object is both on the radio-optical correlation and does not show any UV excess, typical of thermal disk emission, further constrains its origin as being due to nonthermal synchrotron radiation, as it is for FR I nuclei. This also rules out the possibility that its CCC emission is produced by a compact scattering region, reflecting the presence of a hidden quasar in its nucleus, since quite flat values of \( \alpha_{\text{opt,UV}} \) should be observed in that case. The synchrotron origin of its nuclear emission together with the lack of strong emission lines in its spectrum lead us to identify 3C 388 as a “parent source” for BL Lac objects, in agreement with the “dual-population scheme” (Jackson & Wall 1999).

5.3. Variability

Spectral variability is a common characteristic of both synchrotron- and disk-dominated sources. In particular, highly beamed nonthermal sources such as BL Lac objects show dramatic variations on all timescales (from minutes to years). Since the relativistic beaming factor is expected to be significantly lower in radio galaxies, such behavior is expected to be present, although on longer timescales. Clearly, this might strongly affect the determination of the spectral slope. Therefore, it is important to use, where available, simultaneous observations.

Only three sources in our sample (3C 78, 3C 264, and 3C 317) have simultaneous (within a few hours) optical-UV data, while for 3C 274, the time lag between optical and UV observations is only \( \sim 6 \) days. In addition to with the Faint Object Camera (FOC), 3C 317 has also been observed as part of the STIS UV SNAPSHOT program. Interestingly, we have found that the flux of the CCC in the STIS observation is \( 5.1 \times 10^{-17} \) erg s\(^{-1}\) cm\(^{-2}\) A\(^{-1}\), a factor of \( \sim 10 \) brighter than in the FOC observation of 1994. Such a high variability factor indeed strongly supports the nonthermal synchrotron scenario. Variability has also been detected in the optical band in 3C 274, although with much lower intensity (Tsvetanov et al. 1998).

The determination of the spectral slopes of objects for which no simultaneous data are available might be significantly affected by variability. However, we are confident that the general behavior of the CCCs is correctly represented by our estimates. For the BLRGs, this is mainly supported by the fact that all of them show similar spectral indices. For the FR I galaxies, both their position in the plane of Figure 4 and the close connection between steep \( \alpha_{\text{opt,UV}} \) and the presence of obscuring structures are strong clues that obscuration and not variability is indeed the main physical reason for the observed steep slopes.

We conclude that the general behavior is well represented by the picture outlined above, although we cannot definitively rule out the possible presence of variability in individual sources.

6. SUMMARY AND CONCLUSIONS

We have analyzed images of 28 nearby 3C radio galaxies for which both optical and UV HST images are available. We have found that all objects that show an UV CCC also show it in the optical. Only two galaxies (of the FR I type) that have a CCC do not have its UV counterpart. These missing nuclei seem to be associated with the presence of extended (~100 pc scale) dusty disks that are seen almost edge-on in these galaxies and might absorb the nuclear emission in the UV band. However, as the nuclei are clearly seen in the optical, the amount of absorption must be small, and not comparable to the much higher column densities characterizing absorbing tori in other classes of AGNs. The high detection rate of unresolved nuclei in the UV among FR I sources further indicates that their nuclei are generally seen directly, and absorbing tori are not a common characteristic among such low-power radio galaxies.

Of the FR II galaxies, three are classified as broad-line radio galaxies and show the brightest nuclei. The only non–broad-line FR II galaxy that shows a (fainter) CCC is 3C 388, which is classified as an LEG.

We have shown that by combining the UV data with the already available optical and radio information, we can further investigate the origin of these nuclei. In a plane formed by the optical-UV spectral index versus the optical excess with respect to the radio core emission, CCCs occupy different regions. This can be well explained if their position in

\footnote{3C 317 was observed by STIS NUV-MAMA, with the F25SRF2 filter, on 1999 July 27.}
such a plane is strictly connected to the emission process. In particular, the bright nuclei of broad-line FR II galaxies are explained with thermal emission from the accretion disk, while the other CCCs (all FR I galaxies and one FR II galaxy, 3C 388) are compatible with being originated by synchrotron radiation from the jet. The strong variability found in the case of 3C 317 is a further clue of its synchrotron jet origin.

A major result of this work is that only a moderate amount of absorption, whose magnitude appears to be linked to the orientation of the source, is needed to account for the wide range of $\alpha_{\text{UV}}$ spanned by FR I nuclei. Extinction can be higher than $A_V \sim 1–2$ only in highly misoriented galaxies that clearly show extended dusty structures. This indeed constitutes the first direct evidence of nuclear absorption in FR I radio galaxies. Although supported by the presence of only one object, it appears that 3C 388 belongs to a class of FR II galaxies with FR I–like nuclei, in agreement with previous findings. In the framework of the unification models, these objects might well represent the parent population of BL Lac objects with an FR II radio galaxy morphology and power (Kollgaard et al. 1996; Cassaro et al. 1999).

FR II galaxies in which no nuclear source is seen are expected in the frame of the unification models, and we have found 11 FR II galaxies with no UV CCC that might be the obscured counterparts of BLRGs. However, in order to firmly establish their role, a detailed comparison of other properties of these sources (e.g., emission lines, X-ray spectra, extended power and morphology) with those of the unabsorbed FR II galaxies has to be carried out. If they indeed harbor an obscured quasar nucleus, these galaxies should also show strong IR nuclear components, as was found (at 10 $\mu$m) for 3C 405 (Whysong & Antonucci 2001). Unfortunately, the incompleteness of the sample prevents us from drawing any conclusion on the geometry and covering factor of the obscuring material based on the relative number counts of obscured and unobscured objects.

These results provide further support for the idea that the nuclear structure of FR I galaxies is different from other AGNs, in which signatures of the presence of nuclear optically thick dusty tori are often found. In these low-power radio galaxies, the absorbing material cannot be distributed as either a spherical structure or a thin disk in which the absorbing material is well confined. The extended dusty disks often observed in such galaxies can well account for their observed properties. Having assessed the nature of the nuclear emission, the study of the possible connection between the extended dusty structures, the feeding mechanism of the central black hole, and the nature of the accretion process in the different classes of radio galaxies is a promising future perspective for this work.

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