The Chandra view of the 3C/FR I sample of low luminosity radio-galaxies

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Abstract. We present results from Chandra observations of the 3C/FR I sample of low luminosity radio-galaxies. We detected a power-law nuclear component in 12 objects out of the 18 with available data. In 4 galaxies we detected nuclear X-ray absorption at a level of \( N_H \sim (0.2 - 6) \times 10^{22} \text{ cm}^{-2} \). X-ray absorbed sources are associated with the presence of highly inclined dusty disks (or dust filaments projected onto the nuclei) seen in the HST images. This suggests the existence of a flattened X-ray absorber, but of much lower optical depth than in classical obscuring tori. We thus have an un-obstructed view toward most FR I nuclei while absorption plays only a marginal role in the remaining objects. Three pieces of evidence support an interpretation for a jet origin for the X-ray cores: i) the presence of strong correlations between the nuclear luminosities in the radio, optical and X-ray bands, extending over 4 orders of magnitude and with a much smaller dispersion (\( \sim 0.3 \text{ dex} \)) when compared to similar trends found for other classes of AGNs, pointing to a common origin for the emission in the three bands; ii) the close similarity of the broadband spectral indices with the sub-class of BL Lac objects sharing the same range of extended radio-luminosity, in accord with the FR I/BL Lacs unified model; iii) the presence of a common luminosity evolution of spectral indices in both FR I and BL Lacs. The low luminosities of the X-ray nuclei, regardless of their origin, strengthens the interpretation of low efficiency accretion in low luminosity radio-galaxies.

Key words. galaxies : active – galaxies : BL Lacertae objects – galaxies : nuclei – galaxies : jets

1. Introduction

By exploring the properties of low luminosity radio-galaxies (LLRG) it is possible to extend the study of active galactic nuclei (AGN), and in particular of the radio-loud sub-population, toward the lowest level of nuclear luminosity. This offers the opportunity to improve our understanding of the mechanism of accretion onto supermassive black holes and of their radiative manifestations. In this respect, it is important to note that LLRG not only represent the bulk of radio-loud active galaxies, due to the steepness of their luminosity function, but also a substantial fraction of the overall galaxies population. In fact LLRG are associated to a fraction as high as 40% of all bright elliptical and lenticular galaxies (Sadler et al. 1989, Auriemma et al. 1977). Thus the presence of a low power radio-galaxy represents by far the most common manifestation of nuclear activity in early type galaxies.

Low luminosity AGN (LLAGN) also represent a link between the high luminosity AGN and the population of quiescent galaxies, as it is now widely recognized that most (if not all) galaxies host a super-massive black-hole (e.g. Kormendy & Richstone 1995). The comparison of the different manifestations of nuclear activity across the largest possible range of luminosity is then a crucial step to unveil the connections (and the diversities) between active and non-active galaxies.

Unfortunately, the study of LLRG has been significantly hampered by the contamination from host galaxy emission which, in most observing bands, dominates the emission from the AGN. To constrain the physical processes at work in these objects it is clearly necessary to disentangle the AGN and host’s contributions via spectral decomposition or high resolution imaging. In the last few years, thanks in particular to the Hubble Space Telescope (HST) this has become routinely possible.
An example of the insights that can be obtained following this approach comes from the analysis of broad-band HST imaging of a sample of LLRG (Chiaberge et al. 1999). In the majority of the targets, HST images revealed the presence of unresolved optical nuclei. Fluxes and luminosities of these sources show a tight correlation with the radio cores, extending over four orders of magnitude. This has been interpreted as being due to a common non-thermal emission process in the radio and optical band, i.e. that we are seeing the optical emission from the base of a relativistic jet. The low luminosity of LLRG optical nuclei, and the possible dominance of the emission related to out-flowing material, indicates a low level of accretion and/or a low radiative efficiency with respect to classical, more luminous AGN. The high fraction (∼ 85 %) of objects with detected optical nuclear sources suggests a general lack of obscuring molecular tori, a further distinction with respect to other classes of AGN.

The tenuous torus structure, when considered together with the low accretion rate, the low mass of the compact emission line regions (10 - 10$^3 M_{\odot}$) and the limits to the mass of the Broad Line Region ($M_{BLR} < 10^{-2} M_{\odot}$), indicates that a general paucity of gas in the innermost regions of LLRG emerges as the main characterizing difference from more powerful AGN (Capetti et al. 2005).

The advent of Chandra provides us with the unique opportunity to extend the study of LLRG to the X-ray band since its high spatial resolution enables us to isolate any low power nuclear source associated to LLRG. Furthermore, with respect to the optical data, the spectral capabilities of Chandra allow us to study directly the spectral behaviour of the X-ray nuclei. This can be used to quantify the effects of local absorption as well as the slope of their high energy emission as to better constrain the emission processes at work in these sources, particularly when combined in a multi-wavelength analysis using also optical and radio observations. This approach was already followed by several authors in the past (e.g. Capetti et al. 2000, Hardcastle & Worrall 2000, Trussoni et al. 2003, Hardcastle et al. 2003) but clearly, the superior capabilities of Chandra warrant to re-explore this issue in much greater depth.

Here we present results obtained from the analysis of Chandra data for the sample of LLRG drawn from the 3C catalogue of radio-sources (Bennett 1962), more specifically those with a morphological classification as FR I (Fanaroff & Riley 1974). Considering LLRG from the 3C sample, the same studied by Chiaberge et al. (1994) represents an obvious choice. It is the best studied sample of radio-loud galaxies in existence with a vast suite of ground and spaced based observations for comparison at essentially all accessible wavelengths. Other samples of LLRG have been considered in the literature, but, not surprisingly, the coverage provided by Chandra observations for these samples is severely incomplete. For example, only about 10 % of B2 sample of LLRG (Colla et al. 1975) has been observed with Chandra (to be compared to the ∼ 55 % for the 3C/FR I sample), and the analysis is further obstructed by the unknown selection biases introduced in the choice of the individual targets. Similarly we preferred to focus on the Chandra data alone, to provide the highest possible level of uniformity in the analysis.

The paper is organized as follows: in Sec. 2 we present the observations and the data reduction that lead to the results described in Sec. 3 and in particular to the detection of X-ray nuclei in most FR I. In Sec. 4 we explore the effects of the nuclear X-ray absorption, by also relating it to the presence of dust features seen in the HST images. The origin of the X-ray nuclei found in LLRG is explored in Sec. 5. The results are discussed and summarized in Sec. 6.

We adopted $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$.

2. Chandra data analysis

We selected the same sample considered by Chiaberge et al. (1999) formed by the 33 radio-sources from the 3CR catalogue with FR I morphology\footnote{The only addition is 3C 189, which is an FR I part of the 3C sample (Edge et al. 1959) but not of its revised version 3CR (Bennett 1962).}.

We searched for Chandra observations available in the public archive up to January 2005 and we found data for 18 objects (see Table 1). All observations we considered were made using the Advanced CCD Imaging Spectrometer (ACIS-I and ACIS-S) without any transmission grating in place. When more than one observation was available, we generally choose the one with the longer exposure times; only for 3C 338 two observations of approximately equal length were present and they were fitted simultaneously. For the brightest objects instead we choose the observation with the lowest time frame, to reduce the pile-up effect.

We reduced all the data using the Chandra data analysis CIAO v3.0.2, with the CALDB version 2.25. Therefore, to correct for the QE degradation we create a new ARF (effective area files) using the new file `acisD1999-08-13contamN0003.fits' released with the CALDB version 2.26 (as recommended by the “ACIS Modeling and Analysis Team”). We reprocessed all the data from level 1 to level 2, using the CIAO tool acis_process_event with all parameters restored to the default values, i.e. applying the pixels and PHA randomization. The new event file were filtered selecting a standard set of ASCA grades (02346) and rejecting time interval of high background levels.

Our aim is the study of the X-ray emission associated to the AGN. For this reason we choose as extracting region a circle of 1" radius centered on the emission peak (for the fainter nuclei we checked their position using HST or VLA observation) and as background region a source-centered annulus with radii between 1" and 2.5". When X-ray emission from an extended jet is present, we excluded from the background region the corresponding angular portion. With this strategy we aim at reducing as much as possible...
the diffuse thermal X-ray component, as to maximize the nuclear contribution.

A possible drawback of this approach, i.e. a small extraction region, is related to the variations of the Point Spread Function with energy. These might cause the inclusion of a varying fraction of the nuclear emission in our aperture in the different bands. However, we tested that the PSF effects are negligible. In particular the fraction of nuclear counts falling in the background annulus decreases only from $\sim 8\%$ in the 0.5-2 keV band to $\sim 2\%$ in the 2-5 keV band. This has a marginal impact on the derived luminosities and spectral indices.

The spectra were modeled using XSPEC version 11.3.0. We used only events with energy $>0.5$ keV, where the calibration is best known and the background contribution is negligible. We rebinned the spectrum to a minimum of 25 counts per bin in order to ensure the applicability of the $\chi^2$ statistics. We modeled all the spectra with a superposition of a thermal and a power-law (non-thermal) component. For the thermal component the metal abundances were fixed to 0.5 (Fabbiano 1989) and the absorption was set to the galactic value; for the power-law component we allowed for the presence of local absorption. The relative complexity of the model prevents us from obtaining a robust estimate of all free parameters for the sources with a low count rate. More quantitatively, we experimented that only for the twelve objects for which the spectrum can be regrouped in at least 15 channels, as to leave us with $\sim 10$ degree of freedom, corresponding to approximately 400 total net counts, the fit is sufficiently constrained. In the six sources below this threshold we set upper limits for the non-thermal fluxes fitting their spectra using only a power-law model (with column density fixed at the galactic level). We initially fixed the power-law index to 2 but, to be conservative, we then look for the value of Gamma in the range 1.5 - 2.5 corresponding to the largest flux value.

This is a quite conservative approach but our choice it is supported by the fact that in these objects we cannot accurately disentangle the contribution of the thermal and non-thermal components; a less cautious analysis is prone to lead to highly uncertain estimates in particular of the AGN X-ray flux. For the 3 brightest sources (3C 78, 3C 84 and 3C 274) we included the correction for the effects of the pile-up applying the algorithm proposed by Davis (2001). The results of the fit are given in Table 2.

For the 12 objects in which we performed a two components fit, we tested with an F-test$^2$ that the presence of both a thermal component and non-thermal always corresponded to an improvement of the fit at a level $> 95\%$.

Errors and upper limits are quoted at 90% confidence for one parameter of interest ($\Delta \chi^2=2.71$), with the exception of $N_H^2$ and $\Gamma$, well known to be strongly coupled, for which we used a 90% confidence level for two parameters of interest ($\Delta \chi^2=4.61$). Donato et al. (2004) considered X-ray observations of a sample of low luminosity radio-galaxies, largely overlapping with the objects discussed here. With the exception of 3C 338, 3C 348 and 3C 449, which we more conservatively defined as upper limits, there is a complete agreement between the two lists of detected X-ray nuclei. Also the temperature of the thermal component as well as the power-law spectral index are in very good accord when they are measured from Chandra data. Considering the values of $N_H^2$, since we treated more conservatively the errors on this quantity, we obtained upper limits in a few objects which Donato et al. considered as detection of local absorption.

### Table 1. Log of the observation.

| Name   | Obs Id | Inst | Exp time [ks] | Frame time [s] |
|--------|--------|------|---------------|----------------|
| 3C 028 | 3233   | ACIS/I | 50.38        | 3.1            |
| 3C 031 | 2147   | ACIS/S | 44.98        | 3.2            |
| 3C 066B| 828    | ACIS/S | 45.17        | 1.5            |
| 3C 075 | 4181   | ACIS/I | 21.78        | 3.2            |
| 3C 078 | 3128   | ACIS/S | 5.23         | 3.1            |
| 3C 083.1| 3237 | ACIS/S | 95.14        | 3.1            |
| 3C 084 | 3404   | ACIS/S | 5.86         | 0.4            |
| 3C 189 | 858    | ACIS/S | 8.26         | 0.8            |
| 3C 270 | 834    | ACIS/S | 35.18        | 1.8            |
| 3C 272.1| 803  | ACIS/S | 28.85        | 3.2            |
| 3C 274 | 1808   | ACIS/S | 14.17        | 0.4            |
| 3C 296 | 3968   | ACIS/S | 50.08        | 3.2            |
| 3C 317 | 890    | ACIS/S | 37.23        | 3.2            |
| 3C 338 | 497    | ACIS/S | 19.72        | 3.2            |
| 3C 346 | 3129   | ACIS/S | 46.69        | 0.8            |
| 3C 348 | 1625   | ACIS/S | 15.00        | 3.2            |
| 3C 438 | 3967   | ACIS/S | 47.9         | 3.1            |
| 3C 449 | 4057   | ACIS/S | 29.56        | 3.2            |

3. Results

Before we proceed to discuss our results, it is important to note that, since archival data are available for a fraction of about half of the original sample of 3C/FR I, it is possible that we are not considering an unbiased sub-sample. We therefore compared various parameters (e.g. redshift, core and total radio-power) for the 3C/FR I sample as a whole and for our sub-sample. Applying a Kolmogorov-Smirnov test we found that their distributions are consistent with being drawn from the same population with probability always larger than 60 %. Only considering the fraction of optically nucleated galaxies in the Chandra sub-sample is slightly larger, being 83% to be compared to a 70 % for the whole sample (Chiaberge et al. 1999). Overall, it

$^2$ Protassov et al. (2002) suggested that it might inappropriate to use the F-test to test an added spectral component. However, because at the moment there is not known any other simple alternative method, we decided in any case to apply the F-test, above all considering that the presence of an extended thermal emission and a point-like nuclear source are also directly attested by the image.
Table 2. Results of the fit: (1) source name, (2) Galactic hydrogen column density \(10^{22} \text{cm}^{-2}\), (3) local hydrogen column density \(10^{22} \text{cm}^{-2}\), (4) power-law photon index \(\Gamma\), (5) temperature of the thermal component [keV], (6) observed flux of the thermal component corrected for Galactic absorption [erg cm\(^{-2}\) s\(^{-1}\)], (7) non-thermal nuclear flux (corrected for absorption) at 1 keV [erg cm\(^{-2}\) s\(^{-1}\)], (8) \(\chi^2\)/degrees of freedom. When the number of d.o.f. was smaller than 10, no fit was performed. * marks sources affected by pile-up and corrected with the Davies's algorithm.

| Name   | \(N_{H, \text{gal}}\) | \(N_{j}\) | \(\Gamma\) | KT | \(F_x, \text{ther} (0.5-5 \text{ keV})\) | \(F_x, \text{nuc} (1 \text{ keV})\) | \(\chi^2/dof\) |
|--------|-----------------|-----------------|-----|----|-------------------------------|-------------------------------|--------|
| 3C 028 | 0.05            | 0.05            | 0.05 | 0.05 | \(< 1.5 \times 10^{-14}\)     | \(< 3 \times 10^{-14}\)     | \(< 0.01\) |
| 3C 031 | 0.05            | 0.05            | 0.05 | 0.05 | \(< 6 \times 10^{-14}\)     | \(< 1.5 \times 10^{-14}\)     | \(< 0.01\) |
| 3C 066B| 0.09            | 0.09            | 0.09 | 0.09 | \(< 1.5 \times 10^{-14}\)     | \(< 3 \times 10^{-14}\)     | \(< 0.01\) |
| 3C 075 | 0.09            | 0.09            | 0.09 | 0.09 | \(< 1.5 \times 10^{-14}\)     | \(< 3 \times 10^{-14}\)     | \(< 0.01\) |
| 3C 080*| 0.10            | 0.10            | 0.10 | 0.10 | \(< 1.5 \times 10^{-14}\)     | \(< 3 \times 10^{-14}\)     | \(< 0.01\) |
| 3C 083.1| 0.15            | 0.15            | 0.15 | 0.15 | \(< 1.5 \times 10^{-14}\)     | \(< 3 \times 10^{-14}\)     | \(< 0.01\) |
| 3C 084*| 0.15            | 0.15            | 0.15 | 0.15 | \(< 1.5 \times 10^{-14}\)     | \(< 3 \times 10^{-14}\)     | \(< 0.01\) |
| 3C 189 | 0.05            | 0.05            | 0.05 | 0.05 | \(< 1.5 \times 10^{-14}\)     | \(< 3 \times 10^{-14}\)     | \(< 0.01\) |
| 3C 346 | 0.05            | 0.05            | 0.05 | 0.05 | \(< 1.5 \times 10^{-14}\)     | \(< 3 \times 10^{-14}\)     | \(< 0.01\) |
| 3C 488 | 0.11            | 0.11            | 0.11 | 0.11 | \(< 1.5 \times 10^{-14}\)     | \(< 3 \times 10^{-14}\)     | \(< 0.01\) |

Table 3. Summary of radio, optical and X-ray data of the sample: (1) source name, (2) redshift of the galaxy, (3) nuclear radio flux at 5 GHz [mJy], (4) nuclear radio luminosity at 5 GHz [erg s\(^{-1}\)], (5) extended radio luminosity at 178 MHz [erg s\(^{-1}\)], (6) optical nuclear luminosity at 5500 Å [erg s\(^{-1}\)], (7) unabsorbed X-ray nuclear flux (0.5-5 keV) [erg cm\(^{-2}\) s\(^{-1}\)], (8) X-ray nuclear luminosity (0.5-5 keV) corrected for absorption [erg s\(^{-1}\)]. Note: Information about redshift, core radio flux, extended radio emission, optical luminosities are from [Chiaberge et al., 1999]. We adopt an optical spectral index \(\alpha_o = 1\).

| Name   | Redshift | \(F_c\) (5 GHz) | \(\nu L_5\) (5 GHz) | \(\nu L_3\) (178 MHz) | \(\nu L_6\) | \(F_x\) (0.5-5 keV) | \(L_x\) (0.5-5 keV) |
|--------|----------|-----------------|-----------------|-----------------|--------|-----------------|-----------------|
| 3C 028 | 0.1952   | \(< 0.2\)       | \(< 7.3 \times 10^{38}\) | 2.1 E42         | \(< 1.3 \times 10^{-14}\) | \(< 3.4 \times 10^{-14}\) | \(< 2.5 E42\) |
| 3C 031 | 0.01699 | 92.0            | 2.5 E39         | 1.6 E40         | 4.5 E40 | 6.2 E40         | 3.4 E40         |
| 3C 066B| 0.0215 | 182.0            | 8.0 E39         | 3.8 E40         | 2.4 E41 | 2.4 E41         | 2.1 E41         |
| 3C 075 | 0.0232 | 39.0            | 2.0 E39         | 1.9 E40         | \(< 8.3 \times 10^{-14}\) | \(< 8.5 \times 10^{-14}\) | \(< 0.01\) |
| 3C 078 | 0.0288 | 964.0            | 7.6 E40         | 5.5 E40         | 2.1 E42 | 8.8 E40         | 1.4 E42         |
| 3C 083.1| 0.0251 | 21.0            | 1.3 E39         | 5.7 E40         | 9.3 E40 | 1.3 E40         | 1.6 E41         |
| 3C 084 | 0.0176 | 4237.00         | 1.2 E42         | 4.2 E40         | 4.2 E40 | 6.1 E40         | 3.6 E40         |
| 3C 189 | 0.043 | 195.0            | 3.4 E40         | 7.1 E40         | 6.2 E41 | 2.8 E40         | 9.5 E41         |
| 3C 270 | 0.0074 | 308.0            | 1.6 E39         | 1.0 E40         | 2.9 E39 | 4.4 E40         | 4.6 E40         |
| 3C 272.1| 0.0037 | 180.0            | 2.3 E38         | 9.0 E38         | 8.5 E39 | 1.5 E40         | 3.9 E39         |
| 3C 274 | 0.0037 | 4000.0          | 5.2 E39         | 4.9 E40         | 5.6 E40 | 1.3 E40         | 3.4 E40         |
| 3C 296 | 0.0237 | 77.0            | 4.1 E39         | 2.5 E40         | 2.0 E40 | 1.8 E40         | 1.9 E41         |
| 3C 317 | 0.0342 | 391.0            | 4.4 E40         | 1.9 E41         | 1.2 E41 | 1.5 E40         | 3.3 E40         |
| 3C 338 | 0.0303 | 105.0            | 9.2 E39         | 1.4 E41         | 9.7 E40 | \(< 7.6 \times 10^{-14}\) | \(< 1.3 E41\) |
| 3C 346 | 0.1620 | 220.0            | 5.5 E41         | 9.7 E41         | 6.4 E42 | 4.0 E40         | 2.0 E40         |
| 3C 348 | 0.1540 | 10.0            | 2.3 E40         | 2.8 E41         | 2.0 E41 | \(< 7.3 \times 10^{-14}\) | \(< 3.3 E42\) |
| 3C 438 | 0.2900 | 17.0            | 1.4 E41         | 1.3 E43         | \(< 3.5 E4\) | \(< 3.4 \times 10^{-14}\) | \(< 5.4 E42\) |
| 3C 449 | 0.0181 | 37.0            | 1.1 E39         | 1.3 E40         | 6.2 E40 | \(< 4.8 \times 10^{-14}\) | \(< 3.0 E40\) |

appears that the galaxies studied here are well representative of the entire 3C/FRI sample. On the other hand, several galaxies with somewhat peculiar radio-morphology are excluded, (e.g. the fat double 3C 314.1, the compact radio-source associated to 3C 293, the X-shaped 3C 305, or the complex radio-source in 3C 433) possibly leading to a higher fraction of objects with classical core-jets FR I morphology.
3.1. Local absorption in X-ray nuclei

We obtained a statistically significant estimate for the local column density in four objects (namely 3C 83.1, 3C 270, 3C 272.1 and 3C 296) with values $N_H \sim 0.2 - 6 \times 10^{22}$ cm$^{-2}$. In the other cases (8/12) we find an upper limit to $N_H$ (Table 2) ranging from $0.03 \times 10^{22}$ cm$^{-2}$ to $0.7 \times 10^{22}$ cm$^{-2}$. In Fig. 1 we present a histogram of the values of the intrinsic absorption: the white rectangles represent upper limits, while the black ones are the four detections.

3.2. Relations between radio, optical and X-ray emission.

In Fig. 2 (top left panel) we compare the nuclear fluxes in the radio and X-ray bands. A strong correlation is present: the generalized (including the presence of upper limits) Spearman rank correlation coefficient $\rho = 0.88$ corresponding to a probability that the correlation is not present of $P = 0.001$.

The best linear fits were derived as the bisectrix of the fits using the two quantities as independent variables following the suggestion by Isobe et al. (1990) that this is preferable for problems needing symmetrical treatment of the variables. The presence of upper limits in the independent variable suggests to take advantage of the methods of survival analysis proposed by e.g. Schmitt (1985). However, the drawbacks discussed by Sadler et al. (1989) and, in our specific case, also the non-random distribution of upper limits, disfavour this approach. We therefore preferred to exclude upper limits from the linear regression analysis. Nonetheless we note that, a posteriori, 1) the objects with undetected nuclear component in the X-ray are consistent with the correlation defined by the detections only; 2) the application of the Schmidt methods provides correlation slopes that agree, within the errors, with our estimates.

A similarly tight correlation between radio and X-ray nuclear emission is present also considering luminosities, with $\rho=0.72$ corresponding to a probability $P=0.003$ (see Fig. 2, top right panel): it extends over 4 orders of magnitude, with a slope of $m = 0.91 \pm 0.12$ and a dispersion of 0.39 dex (see Table 4 for a summary of the statistical analysis). We tested the possible influence of redshift in driving this correlation (both quantities depend on $z^2$) estimating the Spearman partial rank coefficient\(^3\). The effect is negligible as the value of $\rho$ is essentially unchanged.

We find a similarly strong connection between the X-ray versus optical nuclear luminosity (Fig. 2, left bottom panel). Again, all X-ray upper limits are consistent with the $L_O$ vs. $L_X$ correlation defined by the detected objects. Conversely, note that all three sources where we measured the largest X-ray absorbing column densities (namely 3C 83.1, 3C 270 and 3C 296) lie significantly above the correlation between $L_O$ and $L_X$. This is not surprising since, while the estimated X-ray fluxes are de-absorbed, the optical measurements are not corrected for the presence of local absorption. Indeed, the location of these X-ray absorbed sources in the $L_O$ - $L_X$ is suggestive of significant absorption also in the optical band. We therefore preferred to re-estimate the correlation omitting these three objects, shown in Fig. 2 with a solid line. We obtain a smaller dispersion of 0.23 dex and a steeper corrected slope, $m = 1.16 \pm 0.09$.

Also in the radio-optical plane $L_r - L_O$ we find a strong correlation as already found by Chiaberge et al. (1999),

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3 The Spearman Partial Rank correlation coefficient estimates the linear correlation coefficient between two variables taking into account the presence of a third. If A and B are both related to the variable z, the Spearman correlation coefficient is $\rho_{AB,z} = \frac{\rho_{AB} - \rho_A \rho_B}{\sqrt{(1 - \rho_A^2)(1 - \rho_B^2)}}$.
see Fig. 2 bottom right panel. Again, the 3 X-ray absorbed sources are located below the best fit, supporting the interpretation for an optical deficit derived from their location in the $L_O - L_X$ plane. Similarly, we re-estimated the correlation excluding the potentially absorbed objects in the optical. The slope of the corrected correlation is $m = 0.82 \pm 0.11$ (very similar to the slope of the correlation found by Chiaberge et al. 1999, $m = 0.88 \pm 0.12$, using the whole 3C/FR I sample) with a dispersion of 0.32 dex.

4. The X-ray absorbing medium in FR I nuclei

In 4 galaxies we obtained a detection of local X-ray absorption. In all cases our estimates of the column density are in close agreement with previously published measure-
ments.\footnote{See Chiaberge et al. (2002) and Donato et al. (2004) for 3C 270; Harris et al. (2002) and Donato et al. (2004) for 3C272.1; Hardcastle et al. (2005) for 3C 296.} It is particularly instructive the inspection of their HST images (see Fig. 3) as they unveil a connection between optical and X-ray absorption. The three sources for which we found the largest X-ray absorption show circumnuclear dusty disk structures, on scales between 300 pc - 1 kpc. All disks are seen at large inclinations, the less in-between optical and X-ray absorption. The three sources for which we found the largest X-ray absorption show circumnuclear dusty disk structures, on scales between 300 pc - 1 kpc. All disks are seen at large inclinations, the less in-

Fig. 3. HST images of the 4 radio-galaxies in which we detected a local X-ray absorption, taken from Chiaberge et al. (1999).
5. A jet-origin for the X-ray cores?

The central issue for our understanding of the properties of LLRG is the origin of their nuclear emission. The analysis of the results presented in Section 3.2 provides several pieces of evidence, presented in the following three subsections, supporting the interpretation that the radio, optical and X-ray cores have a common origin, most likely being produced by the base of a relativistic jet, as already suggested from the analysis of ROSAT and HST data by Worrall & Birkinshaw (1994) and Chiaberge et al. (1999).

5.1. Multiwavelength nuclear correlations

The first indication comes from the presence of the strong correlations between the nuclear luminosities in the three available bands.

A connection between the radio, optical and X-ray radiation is observed also in other classes of AGNs including Seyfert galaxies, radio-galaxies and QSO (see e.g. Falcke et al. 1995). However, the dispersion between the emission in the different bands is substantially larger than observed in our sample. For example, at a given radio luminosity, the X-ray emission spans over 4-5 orders of magnitude; even projecting this correlation in a plane considering also the different black hole masses, the rms is still as large as 0.88 dex (Merloni et al. 2003). These results witness, on the one hand, the close link between accretion and ejection in AGN but, on the other, the relatively large allowed range for the parameters coupling the two processes and their radiative manifestations, e.g. the strength of the magnetic field and the structure of the accretion disk.

Conversely, the rms of the data points for our FR I sample around the best fit are typically a mere factor of 2, despite the large range of luminosities involved. Furthermore, concerning the radio-X correlation, it must also be noted that part of this dispersion certainly arises from the (often substantial) errors associated to (at least) the X-ray luminosities, see Table 2. If one considers that also other effects contribute to the dispersion (e.g. variability in non simultaneous observations) the rms value must be considered as a strict upper limit to the intrinsic dispersion.

Thus our results radically differ from a quantitative point of view from the general trend found in other AGNs and point to a much closer connection, such as a common origin for the radio, optical and X-ray emission.

5.2. Broad band spectral indices

The issue of the origin of the X-ray emission in FR I can also be addressed concentrating on the Spectral Energy Distributions (SED) of FR I compared to those of other classes of AGNs. As a SED behaviour can be parameterized using the broad-band spectral indices, we combined the available data in the different energy bands (scaled to the standard reference values, i.e. the radio at 5 GHz, the optical at 5500 Å and X-ray luminosity at 1 keV) and we calculate the broad-band spectral indices of our objects. They are presented in Table 5 and reproduced graphically in the $(\alpha_{ox} \times \alpha_{ro})$ plane (see Fig. 4). The distribution of spectral indices is in complete agreement with the results obtained by Hardcastle & Worrall (2000), who used ROSAT data for the X-ray measurements.

All FR I sources are confined in the upper left region of this plane and show a remarkable homogeneity in their spectral shapes with $\alpha_{ox} = 1.13 \pm 0.11$, $\alpha_{ro} = 0.77 \pm 0.08$, and $\alpha_{rx} = 0.90 \pm 0.05$. The quoted uncertainties represent the measured dispersions of each index, not considering the X-ray absorbed sources. These latter objects are slightly offset from the remaining of the sample but, as we argued in Sect. 3.2, this can be explained as due to the uncorrected dust absorption for the optical data.

We then compare these values with similar estimates for other classes of AGNs. Not surprisingly, radio quiet quasars have a median values of $\alpha_{ro} = -0.1$ and $\alpha_{rx} = 0.36$ (Elvis et al. 1994) much lower than our radio loud sources and this applies also to the Seyfert nuclei (Ho & Peng 2001). But also the steep spectrum radio loud quasar have significantly smaller values $\alpha_{ro} = 0.46$ and $\alpha_{rx} = 0.71$. These differences in spectral indices correspond to an optical (and X-ray) excess for a given radio core power by a factor between 20 and 40.

Conversely, the FR I sources show a substantial overlap with the region of the plane populated by the Low energy peaked BL Lacs (LBL, Padovani & Giommi 1995), see Fig. 4. For the comparison with BL Lacs we consider

| Name       | $\alpha_{ox}$ | $\alpha_{ro}$ | $\alpha_{rx}$ |
|------------|---------------|---------------|---------------|
| 3C 028     |               |               |               |
| 3C 031     | $1.24^{+0.24}_{-0.33}$ | $0.75 \pm 0.12$ | $0.92^{+0.01}_{-0.07}$ |
| 3C 066B    | $1.13^{+0.58}_{-0.29}$ | $0.71 \pm 0.01$ | $0.85^{+0.10}_{-0.20}$ |
| 3C 075     |               |               | $0.83$         |
| 3C 078     | $1.09^{+0.54}_{-0.48}$ | $0.71 \pm 0.01$ | $0.84^{+0.06}_{-0.16}$ |
| 3C 083     | $0.65^{+0.23}_{-0.20}$ | $0.83 \pm 0.01$ | $0.77^{+0.19}_{-0.12}$ |
| 3C 84      | $1.18^{+0.33}_{-0.18}$ | $0.88 \pm 0.09$ | $0.98^{+0.01}_{-0.11}$ |
| 3C 189     | $1.05^{+0.18}_{-0.13}$ | $0.75 \pm 0.01$ | $0.85^{+0.02}_{-0.05}$ |
| 3C 270     | $0.82^{+0.56}_{-0.56}$ | $0.95 \pm 0.01$ | $0.90^{+0.19}_{-0.13}$ |
| 3C 272.1   | $1.31^{+0.31}_{-0.12}$ | $0.69 \pm 0.01$ | $0.90^{+0.10}_{-0.04}$ |
| 3C 274     | $1.18^{+0.07}_{-0.06}$ | $0.79 \pm 0.02$ | $0.93^{+0.01}_{-0.02}$ |
| 3c 296     | $0.80^{+0.28}_{-0.26}$ | $0.86 \pm 0.04$ | $0.84^{+0.09}_{-0.09}$ |
| 3C 317     | $0.97^{+0.15}_{-0.13}$ | $0.91 \pm 0.04$ | $0.93^{+0.05}_{-0.04}$ |
| 3C 338     | $>1.08$        | $0.80 \pm 0.04$ | $>0.90$        |
| 3C 346     | $0.97^{+0.13}_{-0.13}$ | $0.79 \pm 0.06$ | $0.85^{+0.02}_{-0.02}$ |
| 3C 348     | $>0.68$        | $0.81 \pm 0.06$ | $>0.77$        |
| 3C 438     | $>0.92$        | $>0.92$        |               |
| 3C 449     | $>1.2$         | $0.66 \pm 0.02$ | $>0.86$        |
the radio selected BL Lacs sample derived from the 1Jy catalog [Stickel et al. 1991] and the BL Lac sample selected from the Einstein Slew survey [Elvis et al. 1992; Perlman et al. 1996]. We used the classification into high and low energy peaked BL Lacs (HBL and LBL respectively), as well as their multiwavelength data given by Fossati et al. [1998]. The same result is obtained using BL Lac objects drawn from the Deep X-Ray Radio Blazar Survey (DXRBS) [Padovani et al. 2003].

In BL Lacs the emission process is well established and the whole nuclear radiation is ascribed to the base of a relativistic jet. The similarity in the spectral indices distributions of FR I and BL Lac provides further support to the idea that also in FR I the nuclear emission is non-thermal emission associated to an outflow.

A more detailed comparison with LBL is particularly instructive. The unified model for FR I and BL Lacs predicts that these two classes are drawn from the same population and are just seen at different angles with respect to the jet axis. In Fig. 5 we compare the spectral indices of the two groups taking also into account the extended radio-luminosity $L_{\text{ext}}$. Being an isotropic quantity $L_{\text{ext}}$ does not depend on orientation and indeed LBL and FR I share the same range of $L_{\text{ext}}$. Thus FR I overlap in the spectral indices plane with the jet-dominated class with the ‘proper’ level of radio-luminosity.

The differences between FR I and LBL, albeit quite small, warrant further attention to this point. In fact, FR I appear to be located only in the upper left corner characteristic of the LBL region (see Fig. 4). Fig. 5 shows that this is not due to a mismatch of extended radio-luminosity between the two classes. However, as already discussed by Chiaberge et al. [2000] and Trussoni et al. [2003], Doppler beaming not only affects the angular pattern of the jet emission, but it also causes a shift in frequency which in turn modifies the observed spectral indices. It is clearly important to assess if the observed differences between the spectral indices are consistent with this idea.

In Fig. 5, top panel, we give a simplified sketch to graphically illustrate the origin of this effect; we adopted a SED characteristic of a LBL (solid line), with the synchrotron peak in the FIR-mm region and a flat X-ray spectrum. The FR I SED (dotted line, re-normalized for clarity to have the same level of the synchrotron peak as the BL Lac) is shifted at lower energies and this produces a substantial decrease (relative to the radio) in the optical emission. Conversely the X-ray emission is (always relative to the radio) substantially unaltered. Indeed, no significant differences in $\alpha_{\text{rx}}$ between FR I and LBL are present. Given the relatively large errors in the quantities involved in this comparison, and the possible effects of optical absorption described above, we prefer to refrain from a quantitative analysis. Nonetheless, this indicates that the small differences between the spectral indices of FR I and BL Lacs can be qualitatively accounted for with the presence of beaming.

5.3. Spectral indices evolution with luminosity

Fig. 5 provides a further element in favour of a jet origin for the X-ray cores in FR I. Considering both FR I and LBL, a clear trend of the $\alpha_{\text{ro}}$ and $\alpha_{\text{ox}}$ spectral indices with radio luminosity is present: more powerful sources have higher $\alpha_{\text{ro}}$ (and lower $\alpha_{\text{ox}}$) with respect to less luminous objects, while no trend between $\alpha_{\text{rx}}$ and $L_{\text{ext}}$ is apparent. FR I thus appear to follow the same evolution of spectral indices with the extended radio luminosity of LBL.

The slopes of the correlations between radio/optical and optical/X nuclear luminosity provide a different view of the same effect. In Section 3.2 we reported that the dependence of $L_o$ on $L_r$ is flatter than unity ($m=0.82 \pm 0.11$), an indication of an evolution with luminosity of the radio/optical ratio. The opposite behaviour is displayed by the $L_X / L_o$ relationship, which is steeper than unity ($m=1.16 \pm 0.09$).

A dependence of the SED on luminosity, over the whole class of blazar, was recognized by Ghisellini et al. [1998] and it is usually referred to as the “blazar sequence”. Ghisellini et al. [1998] suggested that this is due to a relationship between the positions of the emission peaks with luminosity, related to the increasing cooling effects on the relativistic electrons. In particular, the synchrotron peak
Fig. 5. Broad-band spectral indices plotted versus the extended radio luminosity at 178 MHz for FR I (filled circles) and LBL (triangles). (left) radio/X-ray, (middle) radio-optical and (right) optical/X-ray. The empty circles represent the FR I sources for which we have detected a large \(N_H > 10^{22}\) cm\(^{-2}\) intrinsic X-ray absorption. The solid and dotted lines represent the best linear fit for the changes of the spectral indices with \(L_{ext}\) for FR I and LBL respectively.

shifts at lower frequencies in the most powerful sources. Here we find evidence for a similar sequence among LBL, although it must be pointed out that we here consider the extended radio luminosity while Fossati et al. (1998) used the radio-core luminosity. The optical emission, which in LBL is associated to the decreasing tail of the synchrotron component, would be increasingly reduced with the respect to the radio when the source luminosity increases (see Fig. 4 for a sketch). This accounts for the trend observed in Fig. 4 in LBL. A similar effect is seen also in FR I and suggests the presence of a similar luminosity sequence. This adds further weight to the similarity between BL Lacs and FR I and to a jet origin for the nuclei in radio-galaxies.

6. Summary and conclusions

We presented results from Chandra observations of the 3C/FR I sample of low luminosity radio-galaxies. Data are available for 18 out of the 33 sources of the sample and we detected a power-law nuclear component, the characteristic signature of AGN emission, in 12 objects.

In 4 galaxies we detected nuclear X-ray absorption at a level of \(N_H \sim (0.2 - 6) \times 10^{22}\) cm\(^{-2}\). X-ray absorbed sources are associated with the presence of either highly inclined dusty disks seen in the HST images or to dust filaments directly projected onto the nuclei. Dust is seen also in most of the remaining sources but no X-ray absorption is found with upper limits in the range \(N_H \leq 10^{21} - 10^{22}\) cm\(^{-2}\). This suggests an association between dust (optical) and gas (X-ray) absorption but only when the geometry is favourable, supporting the existence of a flattened absorber, reminiscent of the standard thick tori envisaged by the AGN unified models. However, both the X-ray and (the indirect estimate of) the optical absorption, are substantially smaller when compared to what is typical of e.g. Seyfert galaxies. This indicates that we have an unobstructed view toward most FR I nuclei and that absorption plays only a marginal role in the remaining objects.

Concerning the properties of the obscuring medium, the ratio between optical and X-ray absorption are in the range \(A_V / N_H \sim (0.7 - 3.3) \times 10^{-22}\) mag cm\(^2\), slightly smaller than the standard galactic value, but not as extreme as found in other classes of AGN.

The most important issue is clearly the origin of the X-ray cores which can be produced either by the accretion process or by the associated outflow. Three results support the interpretation for a common origin for the radio, opti-
and X-ray cores, most likely associated to the base of a relativistic jet: i) the presence of strong correlations between the luminosities in the three bands, extending over 4 orders of magnitude and with a much smaller dispersion ($\sim 0.3$ dex) when compared to similar trends found for other classes of AGNs; ii) the close similarity of the broad-band spectral indices with the sub-class of BL Lacs (for which the jet origin is well established) sharing the same range of extended radio-luminosity, in accord with the FR I/BL Lac unified model; iii) the presence of a common evolution of spectral indices with luminosity in both FR I and BL Lacs, most likely due to a shift in the synchrotron emission peak.

In the framework of a jet origin for the optical and X-ray cores, our analysis sets limits to the emission related to accretion at a fraction as small as $10^{-7}$ of the Eddington luminosity, for a $10^9 M_\odot$ black hole. Thus, regardless of the origin of the optical and X-ray nuclei, the luminosity of LLRG in the X-ray band provides further evidence for a low level of accretion and/or for a low radiative efficiency of the accretion process. This was already noted by [Chiaberge et al. 1999] from the analysis of the optical images. The newly measured X-ray luminosities point to the same conclusion with the substantial advantage of being free from the lingering doubts related to i) obscuration for the optical cores, since the X-ray spectra can be directly modeled accounting for the effects of absorption and ii) the possibility that, due to a different SED behaviour with respect to brighter AGN, most of the nuclear emission is shifted at higher energies than the optical, as predicted by models of low efficiency accretion (e.g. [Narayan et al. 2000][Di Matteo et al. 2000]).

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References

Auriemma, C., Perola, G. C., Ekers, R. D., et al. 1977, A&A, 57, 41
Bennett, A. S. 1962, MmRAS, 68, 163
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Bower, G. A., Heckman, T. M., Wilson, A. S., & Richstone, D. O. 1997, ApJ, 483, L33+
Capetti, A., de Ruiter, H. R., Fanti, R., et al. 2000a, A&A, 362, 871
Capetti, A., Kleijn, G. V., & Chiaberge, M. 2005, A&A, 439, 935
Capetti, A., Trussoni, E., Celotti, A., Feretti, L., & Chiaberge, M. 2000b, MNRAS, 318, 493
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chiaberge, M., Capetti, A., & Celotti, A. 1999, A&A, 349, 77
Chiaberge, M., Celotti, A., Capetti, A., & Ghisellini, G. 2000, A&A, 358, 104
Chiaberge, M., Macchetto, F. D., Sparks, W. B., et al. 2002, ApJ, 571, 247
Colla, G., Fanti, C., Fanti, R., et al. 1975, A&AS, 20, 1
Davis, J. E. 2001, ApJ, 562, 575
Di Matteo, T., Quataert, E., Allen, S. W., Narayan, R., & Fabian, A. C. 2000, MNRAS, 311, 507
Donato, D., Sambruna, R. M., & Gliozzi, M. 2004, ApJ, 617, 915
Edge, D. O., Shakeshaft, J. R., McAdam, W. B., Baldwin, J. E., & Archer, S. 1959, MmRAS, 68, 37
Elvis, M., Plummer, D., Schachter, J., & Fabbiano, G. 1992, ApJS, 80, 257
Elvis, M., Wilkes, B. J., McDowell, J. C., et al. 1994, ApJS, 95, 1
Fabbiano, G. 1989, ARA&A, 27, 87
Falcke, H., Malkan, M. A., & Biermann, P. L. 1995, A&A, 298, 375
Fanaroff, B. L. & Riley, J. M. 1974, MNRAS, 167, 31P
Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433
Ghisellini, G., Celotti, A., Fossati, G., Maraschi, L., & Comastri, A. 1998, MNRAS, 301, 451
Hardcastle, M. J. & Worrall, D. M. 2000, MNRAS, 314, 359
Hardcastle, M. J., Worrall, D. M., Birkinshaw, M., & Canosa, C. M. 2003, MNRAS, 338, 176
Ho, L. C. & Peng, C. Y. 2001, ApJ, 555, 650
Huchra, J. & Burg, R. 1992, ApJ, 393, 90
Isebe, T., Feigelson, E. D., Akritas, M. G., & Babu, G. J. 1990, ApJ, 364, 104
Jaffe, W., Ford, H., Ferrarase, L., van den Bosch, F., & O’Connell, R. W. 1996, ApJ, 460, 214
Kormendy, J. & Richstone, D. 1995, ARA&A, 33, 581
Maiolino, R., Marconi, A., Salvati, M., et al. 2001, A&A, 365, 28
Meroni, A., Heinz, S., & di Matteo, T. 2003, MNRAS, 345, 1057
Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2000, ApJ, 539, 798
Osterbrock, D. E. & Martel, A. 1993, ApJ, 414, 552
Padovani, P. & Giommi, P. 1995, ApJ, 444, 567
Padovani, P., Perlman, E. S., Landt, H., Giommi, P., & Perri, M. 2003, ApJ, 588, 128
Perlman, E. S., Stocke, J. T., Schachter, J. F., et al. 1996, ApJS, 104, 251
Risaliti, G., Maiolino, R., & Salvati, M. 1999, ApJ, 522, 157
Sadler, E. M., Jenkins, C. R., & Kotanyi, C. G. 1989, MNRAS, 240, 591
Schmitt, J. H. M. M. 1985, ApJ, 293, 178
Sparks, W. B., Baum, S. A., Biretta, J., Macchetto, F. D., & Martel, A. R. 2000, ApJ, 542, 667
Stickel, M., Fried, J. W., Kuehr, H., Padovani, P., & Urry, C. M. 1991, ApJ, 374, 431
Trussoni, E., Capetti, A., Celotti, A., Chiaberge, M., & Feretti, L. 2003, A&A, 403, 889
Worrall, D. M. & Birkinshaw, M. 1994, ApJ, 427, 134