Stellar populations in a complete sample of local radio galaxies

D. Raimann\textsuperscript{1,2}, T. Storchi-Bergmann\textsuperscript{1}, H. Quintana\textsuperscript{3}, R. Hunstead\textsuperscript{4} and L. Wisotzki\textsuperscript{5} \textsuperscript{*}

\textsuperscript{1} Instituto de Física, Universidade Federal do Rio Grande do Sul, CP15051, Porto Alegre, 91501-970, RS, Brazil
\textsuperscript{2} Universidade do Estado de Santa Catarina – CEO, Rua Arcajú s/n, Pinhalzinho, 89870-000, SC, Brazil
\textsuperscript{3} Facultad de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
\textsuperscript{4} School of Physics, University of Sydney, NSW 2006, Australia
\textsuperscript{5} Astrophysikalisches Institut Potsdam, Potsdam, Germany

ABSTRACT

We investigate the nature of the continuum emission and stellar populations in the inner 1–3 kiloparsecs of a complete sample of twenty-four southern radio galaxies, and compare the results with a control sample of eighteen non-active early-type galaxies. Twelve of the radio galaxies are classified as Fanaroff-Riley type I (FR I), eight as FR II and four as intermediate or undefined type (FR x). Optical long-slit spectra are used to perform spectral synthesis as a function of distance from the nucleus at an average sampling of 0.5–1.0 kpc and quantify the relative contributions of a blue featureless continuum and stellar population components of different ages. Our main finding is a systematic difference between the stellar populations of the radio and control sample galaxies: the former have a larger contribution from an intermediate age (1 Gyr) component, suggesting a connection between the present radio activity and a starburst which occurred \(\sim 1\) Gyr ago. In addition, we find a correlation between the contribution of the 1 Gyr component and the radio power, suggesting that more massive starbursts have led to more powerful radio emission. A similar relation is found between the radio power and the mean age of the stellar population, in the sense that stronger nuclear activity is found in younger galaxies.

We also find that the stellar populations of FR I galaxies are, on average, older and more homogeneous than those of FR IIs. Significant population gradients were found in only four radio galaxies, which are also those with more than 10\% of their total flux at 4020 \AA contributed by age components younger than 100 Myr and/or a featureless continuum (indistinguishable from a 3 Myr old stellar population).

Key words: galaxies:active – galaxies:radio – galaxies: stellar content – galaxies: nuclei

1 INTRODUCTION

The nature of the UV-optical continuum in radio galaxies has been the subject of a number of recent studies (Tadhunter et al. 1996, 2002; Aretxaga et al. 2001; Wills et al. 2002, 2004). While at low redshifts most radio galaxies seem to show stellar populations dominated in the UV-optical by old stars, at high redshifts there is an UV excess, frequently associated with structures that are aligned with the large-scale radio structures, the so-called “alignment effect” (McCarthy et al. 1987; Tadhunter et al. 1996, and references therein).

Several hypotheses have been advanced to explain the alignment effect: episodes of recent star formation associated with the evolution of the host galaxies (Lilly & Longair 1984); star formation episodes triggered by the passage of radio jets through the interstellar medium (Rees 1989); and scattered light from a hidden quasar (Tadhunter et al. 1989; Fabian 1989).

Using detailed spectropolarimetric observations, Tadhunter et al. (1996) demonstrated that the UV-optical continuum of the low-redshift radio galaxy 3C 321 has a multi-component nature. At 3639 \AA, an old stellar population

* E-mail: raimann@if.ufrgs.br; thaisa@if.ufrgs.br; hquintana@astro.puc.cl; rwh@physics.usyd.edu.au; lwisotzki@aip.de
(15 Gyr) contributes 34% of the total flux, an intermediate age population (1 Gyr) contributes another 34%, a hidden quasar provides 22% and a nebular continuum 10%. More recently, Tadhunter et al. (2002) performed a similar study using a larger sample of 22 luminous radio galaxies at intermediate redshifts (0.15 < z < 0.7), mostly composed of Fanaroff & Riley (1974) class II (FR II) radio galaxies. All of them show a UV excess. These results emphasize the multi-component nature of the UV continuum in radio galaxies: only ~1/3 comes from a significant contribution of polarized light (scattered light from a hidden quasar), and the polarization level is never larger than 10%; at 3600 Å, the nebular continuum is present in all objects, with varying proportions of 3–40%; direct AGN light makes a significant contribution in 40% of the objects and a young/intermediate age stellar population (from 0.1 to 2 Gyr) is significant in 15–50% of the radio galaxies.

At lower redshifts, Aretxaga et al. (2001) and Wills et al. (2002, 2004) have found similar results. Aretxaga et al. studied the optical spectra of the nuclei of seven luminous nearby radio galaxies (z < 0.08), which mostly correspond to the FR II class. Three of them show a UV excess. One is a broad-line radio galaxy where the UV excess is mainly due to direct AGN light. In two cases, the blue spectrum is dominated by blue supergiant and/or giant stars with ages from 7 to 40 Myr. Wills et al. (2002) studied the optical spectra of nine FR II radio galaxies (0.05 < z < 0.2). Four galaxies display a UV excess, with one being a broad-line radio galaxy. In the other three, the UV excess is due to young and/or intermediate age stellar populations (from 0.5 to 2 Gyr). The four radio galaxies without UV excess have stellar populations typical of elliptical galaxies. The contribution of the nebular continuum varies from 0 to 26% of the total flux at 3600 Å. No significant contribution from polarized light was found. In a subsequent paper, Wills et al. (2004) performed a similar study on 12 low luminosity FR I radio galaxies (z < 0.2), finding that three objects show UV excess, the main contribution being due to young and/or intermediate age stars.

The studies so far available in the literature refer to samples dominated by FR II galaxies, except for that of Wills et al. (2004) which is constrained to FR I galaxies only. There are no previous studies including a control sample, only a few stellar population studies of early-type galaxies (e.g. Quintana et al. 1990).

The novelty of our present work is three-fold:

1. To minimize selection effects we chose a sample limited in redshift and radio flux, which is complete in the sense that it comprises the closest most luminous radio galaxies. It contains both FR I and FR II radio galaxies.

2. We defined a control sample of early-type galaxies in order to look for systematic differences between the radio galaxies and non-active galaxies of similar Hubble types.

3. We extended the stellar population studies out to a few kiloparsecs from the nucleus, at a sampling of ~0.2–1 kpc.

Our goal was to apply the technique we successfully used in previous studies of stellar populations of Seyfert, LINER and non-active galaxies (Cid-Fernandes et al. 1998; Raimann et al. 2001, 2003, 2004) to address the following questions:

- What fraction of radio galaxies show a UV excess when compared with non-active galaxies of the same Hubble type?
- What is the nature of this UV excess?
- What fraction of radio galaxies exhibit signatures of recent star formation?
- Are there systematic differences between the stellar population of FR I and FR II radio galaxies?
- Are there systematic differences between the stellar population of radio galaxies and non-active galaxies of the same Hubble type?

The paper is organized as follows: In Section 2 we describe the sample galaxies and the observations. In Section 3 we present the measurements of continuum colours, line equivalent widths and their radial variations. We describe the method and results of spectral synthesis in Section 4. In Section 5 we discuss the results, and in Section 6 we present our conclusions.

## 2 SAMPLE AND OBSERVATIONS

### 2.1 Radio galaxies

The sample of radio galaxies comprises 24 objects with z < 0.08 and integrated radio flux density S(408 MHz) > 4.0 Jy, extracted from the Molonglo Southern 4 Jy sample (Burgess & Hunstead, 1994, 2005), with declinations in the range −85° < δ < −30° and galactic latitudes |b| > 10°. The complete sample according to these criteria consists of 30 objects, but we could not observe 6 sources due to poor observational conditions. However, the exclusion of these sources does not seem to bias the survey or affect our conclusions.

In Table I we list the position, morphological type, radio classification (Fanaroff & Riley 1974), emission-line class (see below), apparent magnitude B, S(408 MHz), radial velocity cz and foreground galactic reddening E(B − V)Gal, for each galaxy. 12 radio galaxies are classified as Fanaroff-Riley I (FR I), eight are FR II and four are of intermediate or undefined type (FR x). The emission-line classes have been assigned according to the following criteria: BLRG are radio galaxies with broad emission lines (i.e. permitted emission lines have both narrow and broad-line components); NLRG have narrow emission lines with equivalent widths Wλ > 5 Å; WLRG are the ones with weak emission lines (Wλ < 5 Å); and NO-E have no emission lines. The radial velocities cz range from 8400 to 22500 km s⁻¹, with a mean value of 15000 km s⁻¹ (z ≃ 0.05). The data were extracted from the NASA/IPAC Extragalactic Database (NED).¹

Long-slit spectra of these galaxies were obtained with the EMMI spectrograph at the 3.5m New Technology Telescope (NTT) of the European Southern Observatory (ESO) at La Silla in 2001 September and 2002 February. The spectra were obtained in two segments, covering the wavelength ranges 3500–5000 Å and 4800–7300 Å, at spectral resolutions of 5 and 3.6 Å, respectively. Two exposures were obtained at each spectral region in order to eliminate cosmic rays, yielding total exposure times of 1800 s in the blue region.

¹ The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
2.2 Control sample

The control sample comprises 18 non-active early-type galaxies: 7 lenticulars and 11 ellipticals. They were selected to have similar Hubble types and absolute magnitudes to those of the radio galaxies, and no signs of nuclear activity. In order to be observable with a smaller telescope, the control sample galaxies were selected to be closer ($<0.015$) than the radio galaxies. As we have not used any particular spectral characteristic to build this sample, we believe it is not biased, i.e., the conclusions of this work do not depend on the choice of these galaxies as control sample.

In Table 3, we list the positions, morphological types, apparent magnitudes $B$, radial velocities and foreground galactic reddening values of the control sample.

Long-slit spectra of the control sample were obtained mostly with the Boller & Chivens spectrograph at the 1.52-m telescope at ESO. A few spectra were obtained with the Cassegrain spectrograph at the 4-m Blanco telescope at Cerro Tololo Interamerican Observatory and with the EMMI spectrograph at the 3.5-m NTT at ESO. The wavelength range covered was 3600–7000 Å, at a spectral resolution of 4–6 Å. The slit, with a width corresponding to 1.5′′ on the sky, was oriented along the parallactic angle.

The galaxy NGC 4936 was observed with both the 1.52-m telescope and the NTT in order to check for any systematic differences in the spectra due to different instrumentation. We found none; the results of the measurements and population synthesis are identical for the two datasets within the errors. In order to illustrate this, we kept the entries corresponding to both observations of this galaxy in all the tables of the paper.

A log of these observations is presented in Table 4, where we list the exposure time, the slit position angle, the parallactic angle, air mass, spatial scale, telescope used, and seeing. The mean spatial scale in the control sample is 0.16 kpc/arcsec, a factor $\sim$6 smaller than for the radio galaxy sample.

Two or three exposures of each galaxy were obtained in order to eliminate cosmic rays. The two-dimensional spectra were combined and reduced using standard tasks in IRAF, as for the radio galaxy sample. One-dimensional spectra were extracted in windows of 1.5–3.2 arcsec in the bright nuclear regions and progressively larger windows towards the fainter outer regions.

The spatial coverage ranged between 0.15 and 4 kpc (3–36 arcsec) from the nucleus. The S/N ratio of the extracted spectra ranges between 10 and 30. Fig. 2 shows nuclear and extranuclear spectra of two representative galaxies of the control sample.

Note that the extraction samples smaller regions at the non-active galaxies than at the radio galaxies. Thus, whenever we compare the results for the radio galaxies with those for the control sample galaxies, we combine the nuclear and a few extra-nuclear extractions in the latter in order to cover similar spatial extents in the two samples ($\sim$1 kpc).

3 EQUIVALENT WIDTHS OF ABSORPTION FEATURES AND CONTINUUM COLOURS

The analysis of the stellar population properties was performed using the same principles as in our previous papers (e.g., Raimann et al. 2001, 2003). We constructed a pseudo-continuum at selected pivot-points of the spectra and measured the equivalent widths ($W_{\lambda}$) of eight absorption features. The pivot-points for the continuum are at rest wavelengths 3660, 3780, 4020, 4510, 4630, 5313, 5870, 6080, and 6630 Å and the absorption features we measured are as follows: WLB (a blend of weak lines in the near-UV, within the spectral window $\lambda\lambda$3810–3822 Å), H9 (a blend of absorption lines which includes H9, window $\lambda\lambda$3822–3858 Å), Ca II K ($\lambda\lambda$3908–3952 Å), Ca II H+He (Ca II H at $\lambda\lambda$3952–3988 Å), the CN band ($\lambda\lambda$4150–4214 Å), the G band ($\lambda\lambda$4284–4318 Å), Mg I+Mg II ($\lambda\lambda$5156–5196 Å) and Na I ($\lambda\lambda$5880–5894 Å).

Equivalent widths and continuum definitions are based on Bica & Alloin (1986), Bica (1988), Bica, Alloin & Schmitt (1994) and Raimann et al. (2001). The use of the same set of pivot-points and wavelength windows allows a detailed quantitative analysis of the stellar populations through synthesis techniques, using the spectral library of star clusters of Bica & Alloin (1986) and Bica (1988).

3.1 Nuclear values

A summary of the nuclear measurements for the radio galaxies is presented in Table 5. This table lists the range of equivalent widths and continuum fluxes (relative to that at $\lambda$4020) measured in the nuclear spectra of the radio galaxies. The table also shows, for comparison, the corresponding values for the control sample. For the latter galaxies, nuclear and extranuclear spectra have been combined to cover a spatial extent $\sim$1 kpc, similar to that covered by the nuclear extractions of the radio galaxies. It can be seen that, while the upper limits for the two sub-samples are similar, the radio galaxies have smaller $W_{\lambda}$ on average, indicating the presence of an excess blue continuum. The radio galaxies must either have stellar populations younger or more metal poor than those of the control sample, or nuclear spectra that are diluted by an AGN continuum.

The range of continuum fluxes is also broader in the radio sample, for which both bluer and redder continua are observed relative to the control sample.
when compared with the extranuclear spectra. This dilution is thus probably due to the presence of a featureless continuum (hereafter called FC) being directly observed in these galaxies. Most of the other radio galaxies do not show significant variation in $W_{\lambda}$ along the slit, apart from a weak trend of decreasing $W_{\lambda}$ away from the nucleus. The continuum is generally redder close to the nucleus than outside.

The non-active galaxies of the control sample also show little variation in equivalent width along the slit. Three of the lenticular galaxies from the control sample show stronger gradients, with nuclear equivalent widths $\sim 2\AA$ larger than at 1 kpc from the nucleus. In order to investigate whether the gradients were due to the proximity of these galaxies, thereby providing better spatial sampling, we binned several extracted spatial elements into one, in order to sample the same spatial extent as in the radio galaxies. Even after the binning, the gradients were still present. We thus concluded that the gradients are probably enhanced by the presence of the disk component in the lenticular galaxies. Regarding the continuum, only the control galaxy NGC 2865 has a nuclear continuum bluer than in the extranuclear spectra; the others all have redder nuclear continua.

### 3.2 Radial variations of equivalent widths and continuum colours

The variation of absorption line equivalent widths and continuum colours as a function of distance from the nucleus allows us to study stellar population gradients. In non-active galaxies, the equivalent widths usually increase from the external regions towards the bulge, where they remain approximately constant. The presence of a burst of star-formation and/or a featureless AGN continuum will produce a “dilution” of the absorption lines, with a consequent decrease in equivalent width at the nucleus in comparison with values at adjacent locations (Cid Fernandes et al. 1998).

In Fig. 3, we illustrate the radial variations of $W_{\lambda}$, the continuum flux ratio $F_{4070}/F_{4020}$ and the surface brightness at 4020 Å for two radio galaxies and two control sample galaxies of matched Hubble types. The dotted and dashed vertical lines mark distances at each galaxy of 1 kpc and 3 kpc from the nucleus, respectively. The radio galaxy ESO 075-G41 shows dilution in most equivalent widths and has a bluer continuum at the nucleus than outside, while the radio galaxy MRC B0344−345 does not show dilution and has a redder nucleus than its surroundings. Some $W_{\lambda}$ profiles show a decrease with distance from the nucleus. This latter behaviour is observed also in the control sample galaxies.

In our radio galaxy sample, only the two BLRGs, ESO 075-G41 and Pictor A show clear dilutions of the nuclear equivalent widths and have a bluer nuclear continuum when compared with the extranuclear spectra. This dilution

### 4 THE SPECTRAL SYNTHESIS

Spectral synthesis was performed using the probabilistic formalism described in Cid Fernandes et al. (2001). We reproduced the observed $W_{\lambda}$ and continuum ratios ($C_{\lambda}$) using a base of star cluster spectra with different ages and metallicity.
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Table 2. Observing log for the radio galaxies and spatial scale.

| Name               | P.A.(°)¹ | ψ(°)² | Air mass  | Scale ³ (kpc/°') | Seeing (') | Linear ⁴ (kpc) | Log L_{408} |
|--------------------|----------|-------|-----------|------------------|------------|---------------|-------------|
| ESO 350-G15        | 11       | 106   | 1.02      | 0.91             | 1.2        | 62            | 25.29       |
| NGC 612            | 103      | 105   | 1.07      | 0.56             | 1.2        | 304           | 25.47       |
| ESO 198-G1         | 173      | 148   | 1.07      | 1.15             | 1.2        | 490           | 25.63       |
| ESO 248-G10        | 49       | 5     | 1.04      | 1.13             | 1.1        | 1745          | 25.80       |
| MRC B0332–391      | 100      | 80    | 1.15      | 1.12             | 1.1        | 470           | 25.50       |
| MRC B0344-345      | 105      | 92    | 1.13      | 0.98             | 1.5        | 265           | 25.62       |
| IC 2082            | 109      | 71    | 1.26      | 0.76             | 1.2        | 210           | 25.64       |
| MRC B0429–616      | 14       | 36    | 1.25      | 1.01             | 1.2        | 115           | 25.41       |
| MRC B0456–301      | 103      | 83    | 1.14      | 1.13             | 1.0        | 395           | 25.73       |
| Pictor A           | 102      | 82    | 1.35      | 0.65             | 1.0        | 293           | 25.67       |
| ESO 365-IG6        | 88       | 110   | 1.05      | 0.61             | 1.0        | 60            | 25.07       |
| MRC B0620–526      | 50       | 66    | 1.25      | 0.93             | 1.2        | 296           | 25.65       |
| ESO 161-IG7        | 103      | 65    | 1.29      | 1.00             | 0.9        | 119           | 26.16       |
| MRC B0715–302      | 82       | 90    | 1.22      | 0.60             | 0.7        | 269           | 25.04       |
| ESO 377-G46        | 87       | 71    | 1.05      | 0.63             | 0.9        | 38            | 25.11       |
| ESO 271-G20        | 102      | 117   | 1.18      | 0.96             | 1.2        | 47            | 25.40       |
| MRC B1413–304      | 29       | 109   | 1.05      | 1.32             | 1.0        | 252           | 25.78       |
| MRC B1637–771      | 0        | 40    | 1.60      | 0.79             | 1.4        | 206           | 25.66       |
| ESO 338-IG11       | 134      | 157   | 1.02      | 1.33             | 0.7        | 150           | 25.66       |
| MRC B2013–557      | 155      | 150   | 1.13      | 1.08             | 1.3        | 1300          | 25.52       |
| MRC B2148–555      | 26       | 164   | 1.12      | 0.72             | 1.2        | 560           | 25.20       |
| MRC ESO 075-G41    | 18       | 5     | 1.31      | 0.53             | 0.7        | 42            | 25.97       |
| MRC AM 2158–380    | 40       | 140   | 1.03      | 0.62             | 1.2        | 71            | 24.93       |
| MRC ESO 349-G10    | 141      | 123   | 1.01      | 0.90             | 1.4        | 61            | 25.59       |

¹ Slit position angle
² Parallactic angle
³ Calculated for a flat WMAP cosmology with H₀ = 75 km s⁻¹ Mpc⁻¹
⁴ Linear extent of the radio source

To synthesize the data from the two samples we used the continuum ratios C_{5660} = F(3660)/F(4020), C_{4510} = F(4510)/F(4020), C_{5870} = F(5870)/F(4020), and C_{6630} = F(6630)/F(4020), and the equivalent widths W_{WLB}, W_{WB}, W_{Ca II K}, W_{CN band}, W_{G band} and W_{Mg I+Mg H}. The adopted errors were σ(Wₜ) = 0.4 Å for W_{Mg I+Mg H}, σ(Wₜ) = 0.5 Å.
Figure 1. Sample of nuclear and extranuclear spectra of the radio galaxies: (a) a BLRG; (b) a NLRG; (c) a WLRG and (d) a radio galaxy without emission lines.

for $W_{WLB}$, $W_{H9}$, $W_{Ca II K}$ and $W_{G band}$, $1.0$ Å for $W_{CN band}$ and $\sigma(C_\lambda) = 0.05$ for the continuum ratios (Cid Fernandes et al. 1998). In a few cases the synthesis was performed with a smaller number of equivalent widths, due to contamination from emission lines.

As pointed out by Storchi-Bergmann et al. (2000; see also Cid Fernandes et al. 2001), it is not possible to discriminate the FC component from the 3 Myr young stellar component in this spectral range, for flux contributions smaller than 40\% at 4020 Å, because they have very similar continua. Therefore, in the description and discussion of the synthesis results we have combined the 3 Myr and FC components, which we refer to as the 3 Myr/FC component.

According to Cid Fernandes et al. (2001), this method of spectral synthesis can have difficulty in accurately determining the contributions of all 12 components of Bica’s database when the S/N ratio is modest or there is a reduced number of observables. These constraints act primarily in the sense of spreading a strong contribution in one component preferentially among base elements of different metallicities but of the same age. Therefore, in order to produce more robust results, we have grouped components of different metallicities but of the same age into one component, characterized by that age. We have thus neglected the potential differentiation in metallicity and concentrated on the more robust age information.

In Tables 6 and 7, we present the synthesis results as the relative contributions from components of four age bins to the total flux at 4020 Å: 10 Gyr, 1 Gyr, 100+10 Myr and 3 Myr/FC, in the nuclear region, at 1 kpc, and at 3 kpc from the nucleus, respectively.
Table 4. Log of observations of the control sample.

| Name     | Exp. time(s) | P.A.(°) | ψ(°) | Air mass | kpc/” | Telescope | Seeing (”) |
|----------|--------------|---------|------|----------|-------|-----------|------------|
| NGC1404  | 5400         | 90      | 100  | 1.50     | 0.10  | 1.5m ESO  | 0.8        |
| NGC1700  | 600          | 20      | 13   | 1.10     | 0.25  | 3.6m NTT  | 1.5        |
| NGC2865  | 5400         | 90      | 36   | 1.02     | 0.17  | 1.5m ESO  | 1.0        |
| NGC3091  | 5400         | 90      | 65   | 1.15     | 0.25  | 1.5m ESO  | 0.9        |
| NGC3585  | 5400         | 90      | 150  | 1.01     | 0.09  | 1.5m ESO  | 1.0        |
| NGC3706  | 5400         | 90      | 90   | 1.20     | 0.19  | 1.5m ESO  | 0.9        |
| NGC3904  | 5400         | 90      | 81   | 1.19     | 0.10  | 1.5m ESO  | 0.8        |
| NGC3923  | 5400         | 90      | 96   | 1.00     | 0.12  | 1.5m ESO  | 0.8        |
| NGC4373  | 5400         | 90      | 20   | 1.02     | 0.21  | 1.5m ESO  | 0.8        |
| NGC4825  | 5400         | 90      | 30   | 1.05     | 0.28  | 1.5m ESO  | 0.9        |
| NGC4936  | 5400         | 90      | 90   | 1.01     | 0.19  | 1.5m ESO  | 1.0        |
| NGC4936  | 600          | 86      | 86   | 1.07     | 0.19  | 3.6m NTT  | 1.0        |
| NGC5061  | 5400         | 90      | 78   | 1.10     | 0.17  | 1.5m ESO  | 0.9        |
| NGC5328  | 5400         | 90      | 95   | 1.10     | 0.30  | 1.5m ESO  | 0.8        |
| NGC5813  | 600          | 90      | 90   | 1.25     | 0.13  | 3.6m NTT  | 1.0        |
| NGC6684  | 1800         | 155     | 155  | 1.26     | 0.05  | 4m CTIO   | –          |
| NGC6861  | 1800         | 125     | 125  | 1.14     | 0.18  | 4m CTIO   | –          |
| NGC7049  | 1800         | 116     | 116  | 1.19     | 0.14  | 4m CTIO   | –          |
| NGC7079  | 5400         | 90      | 50   | 1.10     | 0.17  | 1.5m ESO  | 1.5        |

Figure 2. Spectra of an elliptical (a) and a lenticular (b) galaxy from the control sample.

Table 5. Range of nuclear equivalent widths and continuum fluxes from each sub-sample.

| Sample          | $W_{WLB}$ | $W_{H9}$ | $W_{CaII\,K}$ | $W_{CaII\,H+H}$ | $W_{CN}$ | $W_{G}$ | $W_{Mg\,I+Mg\,H}$ | $W_{NaI}$ |
|-----------------|-----------|----------|----------------|-----------------|----------|--------|-------------------|-----------|
| Radio galaxies  | 1–7       | 7–18     | 8–20           | 8–15            | 5–15     | 4–12   | 4–11              | 4–9       |
| Non-active galaxies | 4–7   | 13–20    | 14–20          | 12–14           | 7–12     | 10–19  | 6–12              | 3–7       |
|                 | 3660Å     | 4510Å    | 5870Å          | 6630Å           |          |        |                   |           |
| Radio galaxies  | 0.47–1.22 | 0.83–1.57| 0.74–3.24      | 0.67–3.79       |          |        |                   |           |
| Non-active galaxies | 0.52–0.63| 1.25–1.69| 1.62–2.41      | 1.51–2.40       |          |        |                   |           |
The synthesis results for the radio galaxies are summarized in Table 6. In most of the radio galaxies, the nuclear and extranuclear stellar population is dominated by old (10 Gyr) and intermediate (1 Gyr) age components.

There are only four radio galaxies in which the younger or power-law components contribute more than 10% of the total flux at 4020 Å, either at the nucleus or outside. Two of the latter galaxies are the BLRGs Pictor A and ESO 075-G41, in which the 3 Myr/FC component is probably dominated by the FC, as discussed in previous sections.

For the two BLRG's galaxies, we performed another synthesis after subtracting the contribution of the 3 Myr/FC component, in order to test whether the underlying stellar population was similar to that in the other galaxies. We show the results of this new synthesis in parenthesis in Table 6: the contribution of the 10 Gyr stellar population increases, indeed becoming more similar to that of the other galaxies, but the contribution of the 1 Gyr component does not, thus maintaining the difference from the other galaxies. There is an increase of the contribution of the 100+10 Myr component in the new synthesis. Finally, we point out that, for these galaxies, the synthesis results must be taken with caution, due to the fact that we have assumed a fixed slope for the power-law component (namely \( F_\nu \propto \nu^{-1.5} \)). As this component is very strong in these galaxies, if the real slope is different, it will affect the results of the synthesis. In particular, if the slope is harder than assumed, we may see excess blue light which could appear artificially as a large contribution of the 100+10 Myr component.

### Table 6: Synthesis Results for Radio Galaxies

| Galaxy   | W_{Ca II, K} (Gyr) | W_{Ca II, H\alpha} (Gyr) | W_{Mg II, H\alpha} (Gyr) | W_{H\alpha} (Gyr) | W_{H\beta} (Gyr) | W_{Ca II, H\alpha} (Gyr) |
|---------|-------------------|-------------------------|-------------------------|-------------------|-----------------|-------------------------|
| ESO 075-G41 | 10                | 5                       | 10                      | 0                 | 0               | 0                       |
| Pictor A   | 10                | 5                       | 10                      | 0                 | 0               | 0                       |
| ESO 075-G41 | 10                | 5                       | 10                      | 0                 | 0               | 0                       |

### Figure 3. Radial Variations of Equivalent Width, Continuum Colour and Surface Brightness for Radio Galaxies (top) and Control Sample Galaxies (bottom). The first panel, from top to bottom, shows \( W_{WLB} \) (solid line) and \( W_{H\beta} \) (dotted), the second shows \( W_{Ca II, K} \) (solid) and \( W_{Ca II, H\alpha} \) (dotted), the third, \( W_{G-band} \) (solid) and \( W_{CN-band} \) (dotted), the fourth, \( W_{Mg II, H\alpha} \) (solid) and \( W_{Na I} \) (dotted). The fifth panel shows the continuum flux ratio between 5870 and 4020 Å. The sixth panel shows the run of the surface brightness at 4020 Å (in units of \( 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \text{ arcsec}^{-2} \)) along the slit. The dotted and dashed vertical lines mark distances of 1 kpc and 3 kpc from the nucleus, respectively.
Table 6. Percentage contributions of four age bins to the total flux at 4020 Å for the radio galaxy sample, separated according to their FR classification.

| Name         | 10 Gyr | 1 Gyr | 100+10 Myr | 3 Myr/FC | Mean Age |
|--------------|--------|-------|------------|----------|----------|
|              | 1 kpc  | 3 kpc | 1 kpc      | 3 kpc    | (Gyr)    |
| ESO 350-G15  | 56     | 57    | 55         | 41       | 3        |
| ESO 198-G1   | 53     | 54    | 51         | 44       | 3        |
| IC 2082      | 60     | 54    | 65         | 38       | 2        |
| MRC B0429−616| 50     | 50    | 53         | 42       | 7        |
| MRC B0620−526| 47     | 46    | 45         | 46       | 6        |
| ESO 161-IG7  | 59     | 58    | 53         | 38       | 3        |
| MRC B0715−362| 72     | 61    | 17         | 9        | 2        |
| ESO 377-G46  | 62     | 59    | 35         | 24       | 1        |
| MRC B0456−301| 14     | 13    | 60         | 24       | 2        |
| MRC B0344−345| 63     | 61    | 54         | 29       | 6        |
| MRC B0456−301| 14     | 13    | 60         | 24       | 2        |
| Pictor A     | 21(45) | 49    | 10(14)     | 8        | 12(41)   |
| ESO 365-IG6  | 69     | 68    | 28         | 3        | 3        |
| MRC B1413−364| 63     | 52    | 33         | 3        | 3        |
| MRC B1637−771| 46     | 50    | 48         | 7        | 6        |
| ESO 075-G41  | 39(55) | 46    | 10(13)     | 23       | 24(32)   |
| AM 2158−380  | 69     | 74    | 70         | 25       | 4        |

The 10 Gyr component – In 21 of the 24 radio galaxies the 10 Gyr component contributes from ~50% to 70% of the total flux in the nuclear region. The contribution is smaller only in MRC B0456-301 and in the two BLRGs before the subtraction of the 3Myr/FC component. There is little variation with radius. Only five objects have differences between nuclear and extranuclear contributions larger than 10%. In three cases the contribution of the 10 Gyr component decreases outwards and in the two BLRGs it increases, as expected. After subtraction of the 3Myr/FC component from the spectra of the two BLRGs, the gradient disappears in Pictor A and is weakened in ESO 075-G41.

The I Gyr component – The 1 Gyr component contribution is dominant only in the nuclear spectrum of MRC B0456−301, and it contributes at least ~30% of the total flux in 19 objects. In four objects the difference between nuclear and extranuclear contributions is > 10%, with the contribution of this component increasing outwards.

Younger components – Besides the two BLRGs, the FR x galaxy MRC B0456-301 is the only radio-galaxy which presents, at the nucleus and up to 1 kpc from it, a contribution of the 100+10 Myr component significantly larger than 10%. NGC 612 displays such contribution at 3 kpc from the nucleus, probably triggered by an interaction related to its peculiar morphology. After subtracting the contribution of the 3 Myr/FC component from the spectra of Pictor A and ESO 075-G41, there is an increase of the contribution of the 100+10 Myr component.

Internal reddening – Internal reddening in the radio galaxies is generally small. The only cases of significant reddening, with values in the range 0.06 ≤ E(B−V)int ≤ 0.4, are observed in the FR II/x galaxies NGC 612, ESO 248-G10, ESO 075-G41 and MRC B0344−345, and in the FR I galaxy MRC B2013−557.

Gradients – The 3 Myr/FC component decreases outwards in the two BLRGs, but, as discussed above, this is most probably due to the unresolved FC component. By examining a stellar spatial profile, we concluded that at the angular distance corresponding at the galaxies to 1 kpc, there is still contamination of the spectra by a possible point source at the nucleus. This is the reason why, at 1 kpc, Table 6 shows some contribution from the 3 Myr/FC component. A true stellar population gradient is observed in the FR II galaxy NGC 612, in which the stellar population is predominantly old at the nucleus and there is a 100+10 Myr-old component at a radius of 3 kpc.
Table 7. Percentage contributions of four age bins to the total flux at 4020 Å for elliptical and lenticular galaxies from the control sample.

| Name       | 10 Gyr | 1 kpc | 3 kpc | 1 Gyr | 1 kpc | 3 kpc | 100+10 Myr | 1 kpc | 3 kpc | 3 Myr/FC | 1 kpc | 3 kpc |
|------------|--------|-------|-------|-------|-------|-------|-------------|-------|-------|---------|-------|-------|
| Ellipticals|        |       |       |       |       |       |             |       |       |         |       |       |
| NGC 1404  | 75     | 79    | –     | 22    | 16    | –     | 3            | 5     | –     | 0       | 0     | –     |
| NGC 1700  | 71     | 71    | –     | 22    | 25    | –     | 6            | 3     | –     | 1       | 1     | –     |
| NGC 2865  | 56     | 65    | –     | 24    | 19    | –     | 20           | 15    | –     | 0       | 1     | –     |
| NGC 3091  | 76     | 74    | –     | 15    | 22    | –     | 8            | 4     | –     | 1       | 0     | –     |
| NGC 3585  | 73     | 82    | –     | 20    | 14    | –     | 6            | 4     | –     | 1       | 0     | –     |
| NGC 3904  | 81     | 78    | –     | 15    | 20    | –     | 3            | 2     | –     | 1       | 0     | –     |
| NGC 3923  | 69     | 77    | –     | 25    | 19    | –     | 6            | 4     | –     | 0       | 0     | –     |
| NGC 4936  | 75     | 88    | –     | 19    | 10    | –     | 4            | 2     | –     | 2       | 0     | –     |
| NGC 4936  | 81     | 80    | –     | 11    | 16    | –     | 6            | 3     | –     | 2       | 1     | –     |
| NGC 5061  | 70     | 77    | –     | 18    | 16    | –     | 12           | 6     | –     | 0       | 1     | –     |
| NGC 5328  | 66     | 67    | –     | 24    | 18    | –     | 9            | 14    | –     | 1       | 1     | –     |
| NGC 5813  | 83     | –     | –     | 8     | –     | –     | 7            | –     | –     | 2       | –     | –     |
| Lenticulars|        |       |       |       |       |       |             |       |       |         |       |       |
| NGC 3706  | 78     | 76    | –     | 12    | 19    | –     | 8            | 4     | –     | 2       | 1     | –     |
| NGC 4373  | 66     | 68    | –     | 30    | 26    | –     | 4            | 5     | –     | 0       | 1     | –     |
| NGC 4825  | 80     | 81    | 79    | 12    | 12    | 11    | 7            | 6     | 6     | 1       | 1     | 3     |
| NGC 6684  | 66     | 54    | –     | 32    | 43    | –     | 2            | 3     | –     | 0       | 0     | –     |
| NGC 6861  | 67     | 53    | 37    | 27    | 44    | 53    | 6            | 3     | 10    | 0       | 0     | 0     |
| NGC 7049  | 73     | 56    | 34    | 21    | 42    | 62    | 6            | 2     | 3     | 0       | 0     | 1     |
| NGC 7079  | 50     | 45    | –     | 48    | 52    | –     | 2            | 3     | –     | 0       | 0     | –     |

1. 1.5m ESO
2. 3.6 NTT

4.2 Synthesis results for the control sample galaxies

The synthesis results for the control sample galaxies are summarized in Table 7.

The 10 Gyr component – The nuclear and extranuclear stellar populations of the non-active galaxies are dominated by the old (10 Gyr) component, which in most cases contributes 70 to 85 % of the total flux at 4020 Å.

The 1 Gyr component – The intermediate age (1 Gyr) component is also significant in this sample and its contribution in most cases is within the range 15 to 30 %.

Younger age components – There are three non-active galaxies in which the 100+10 Myr component contributes 10 % or more of total flux at 4020 Å, but this contribution is never larger than 20 %. These three galaxies are ellipticals. The 3 Myr/FC component contribution is not significant in any of the galaxies of the control sample.

Reddening – None of the control sample galaxies shows internal reddening larger than $E(B - V)_{int} = 0.05$.

Gradients – In general we do not observe any population gradients in the galaxies of the control sample. Only three lenticular galaxies show differences between the nuclear and extranuclear age components at a level greater than 10 %. In these three cases, the 10 Gyr component contribution decreases while the 1 Gyr contribution increases outwards. We attribute these gradients to the presence of a disk component in these galaxies, as discussed in Section 3.2.

5 DISCUSSION

5.1 Comparison FR I vs. FR II galaxies

In Fig. 4 we compare the population synthesis results of the FR I galaxies with those of the FR II, plus intermediate and uncertain types, for each age component. In each histogram, we show the number of galaxies as a function of the percentage contribution of that age component to the total flux at 4020 Å. We show the results only for the nucleus as we did not find significant spatial variation, as discussed in the previous sections. In Table 8 we list the mean percent contribution of each age bin to the total flux at 4020 Å and the corresponding standard deviations.

The histograms show that the fractional contributions of each age component have a narrower distribution in FR I than in FR II galaxies. In other words, the stellar populations in FR I galaxies are more homogeneous than in FR II galaxies. No FR I galaxy has more than a 10 % contribution from components of age 100 Myr or younger, while four FR II/x galaxies have such components.

The above results translate into mean contributions (Table 8) of the 10 Gyr and 1 Gyr age components slightly larger in FR I than in FR II galaxies. In other words, the stellar populations in FR I galaxies are more homogeneous than in FR II galaxies. No FR I galaxy has more than a 10 % contribution from components of age 100 Myr or younger, while four FR II/x galaxies have such components.

The above results translate into mean contributions (Table 8) of the 10 Gyr and 1 Gyr age components slightly larger in FR I than in FR II galaxies, while the reverse is true for the 100 Myr and younger components. The standard deviations are larger for FR II galaxies in accordance with their broader distributions in Fig. 4.

5.2 Relation with Emission Line Properties

Fig. 5 shows the distribution of fractional contributions of the four age components to the spectra of the radio galaxies where they are identified according to their emission-line
Figure 4. Histograms for the radio galaxies showing the contributions of different age components (10 Gyr, 1 Gyr, 100+10 Myr and 3 Myr/FC) to the total flux at 4020 Å. FR I galaxies are shown as open histograms with a heavy outline and FR II/x are shown hatched.

Table 8. The mean percent contribution (and corresponding standard deviation) to the total flux at 4020 Å for the nuclear stellar populations of the 10 Gyr, 1 Gyr, 100+10 Myr and 3 Myr/FC components.

| Objects                  | 10 Gyr | 1 Gyr | 100+10 Myr | 3 Myr/FC |
|--------------------------|--------|-------|------------|----------|
| FR I radio galaxies      | 57.9 (6.9) | 36.9 (7.4) | 4.4 (2.2) | 0.8 (0.7) |
| FR II/x radio galaxies   | 51.2 (17.7) | 32.5 (14.6) | 8.3 (7.6) | 8.1 (16.4) |
| All radio galaxies       | 54.5 (13.9) | 34.7 (11.8) | 6.3 (5.9) | 4.4 (12.2) |
| Control sample           | 65.4 (17.3) | 24.9 (11.1) | 5.4 (4.1) | 0.6 (0.6) |

spectra (BLRG, NLRG, WLRG and NO-E). The NO-E radio galaxies tend to have the largest contribution from the 10 Gyr stellar component (> 50%), similar to that of the control sample (see section 5.4). The smallest contribution (< 40%) of the 10 Gyr component is observed in the two BLRGs and in the NLRG MRC B0456−301. Most of the NLRGs and WLRGs show intermediate values (40–70%) for contributions of the 10 Gyr component. Regarding the 1 Gyr component, the only clear trend is that the BLRGs have the smallest contributions (< 10%). In the case of the 10 + 100 Myr age component, the only three galaxies with a contribution larger than 10% are the two BLRGs and one NLRG (B0456−301); these are the same three galaxies which show the smallest contribution of the 10 Gyr component. In the case of the 3 Myr/FC component, only the two BLRGs show contributions larger than 10%, which, as noted earlier, we attribute mostly to the FC.

In 13 radio galaxies we were able to measure the flux of the [OIII] λ5007 emission line. In order to investigate the relation between the luminosity $L_{[OIII]}$ in this line and the age of the stellar population, we defined a percentage-weighted “mean age” $\bar{t}$ as the mean decimal logarithm of the stellar population ages used in the synthesis, as follows:

$$\log(\bar{t}) \equiv \sum x_i \log(t_i)$$

where $x_i$ are the fractional contributions to the total flux.
5.3 Relation with Radio Power

Although the radio luminosities do not cover a wide range, we also find some correlation between the radio power and the stellar populations properties of the radio galaxies. We have separated the radio sample into four power bins: \(\leq 2\), 2–4, 4–6 and \(\geq 6 \times 10^{25}\) W \(\text{Hz}^{-1}\). The values of radio power are listed in the last column of Table 2. The distribution of the fractional contributions of the four age components split by radio power is shown in Fig. 6. The galaxies with the lowest radio power tend to have the largest contribution from the 10 Gyr age component, and to have a stellar population mix closest to that of the control sample (see section 5.4). For high radio power, the stellar population properties vary widely.

In order to better quantify the relation between the radio power and the age of the stellar population, we have plotted in Fig. 7 the logarithm of the radio luminosity at 408 MHz, \(\log(L_{408\text{MHz}})\) against the mean age as calculated in the previous section. We observe an inverse relation in

![Figure 5](image1.png)

**Figure 5.** As in Fig. 4 for the radio galaxies identified according to their emission-line spectra: BLRG, NLRG, WLRG and NO-E.

![Figure 7](image2.png)

**Figure 7.** Relation between the luminosity \(\log L_{[\text{OIII}]}\) and the mean age, as defined in the text.
Figure 6. As in Fig. 4 for the radio galaxies identified as a function of radio power (in units of $10^{25}$ W Hz$^{-1}$).

Figure 8. Relation between the log radio power (in units of W Hz$^{-1}$) and the mean age, as defined in the text.

Fig. 8: the most powerful radio sources tend to be found in the youngest galaxies.

In Fig. 9 we show the percentage contribution of each age bin to the total flux at $\lambda$4020 against log($L_{\text{4020 MHz}}$). For most of the sample, there is an inverse relation between the contribution of the 10 Gyr component and the radio power: the most radio luminous galaxies present the smallest contribution of the 10 Gyr component. Only one galaxy does not follow the relation: MRC B0456-301, whose nuclear light is dominated by the contribution of the 1 Gyr and 100+10 Myr components.

There is also a direct relation between the contribution of the 1 Gyr component and radio power: larger radio power corresponds to larger contribution of the 1 Gyr component. The two BLRGs seem to be exceptions to this relation. Nevertheless, as pointed out in Section 4.1, the synthesis in these two cases may be uncertain due to the large contribution of the direct AGN light to the spectrum.

There is no obvious correlation of radio power with the younger age components.

5.4 Radio galaxies vs. control sample

Figure 10 shows comparative histograms for the radio galaxies and control sample galaxies in the percentage contributions of each age component to the flux at 4020 Å of the nuclear spectra. In the lower half of Table 8 we list the mean contributions and corresponding standard deviations.

The histograms and Table 8 show that the main differences between the stellar populations of the radio galaxies...
and control sample are in the relative contributions of the 10 Gyr and 1 Gyr components. In the radio galaxies, the contribution of the 10 Gyr component is systematically smaller, while the contribution of the 1 Gyr component is systematically larger than in the control sample.

The above results suggest that 1 Gyr old star formation episodes have been more frequent in radio galaxies than in non-active galaxies of the same Hubble type, suggesting a relation between star-formation episodes triggered 1 Gyr ago and the presence of radio activity at the present time. In addition, the correlation between the radio power and the contribution of the 1 Gyr component that we found in the previous section suggests that the radio power is correlated with the mass of the starburst.

6 SUMMARY AND CONCLUSIONS

In this paper we have studied the nuclear and extranuclear stellar populations of a complete sample of 24 radio galaxies and a control sample of 18 non-active early-type galaxies, matched in Hubble type to those of the radio sample. The main conclusions of this work can be summarized as follows.

i) In most radio galaxies, the stellar population is dominated by old (10 Gyr) and intermediate age (1 Gyr) components.

ii) Blue continua due to an AGN and/or to recent star formation episodes (100 Myr old or younger) are found in only four of the 24 radio galaxies. Two of them are BLRGs, for which the blue continuum is probably dominated by the AGN light. The frequency of clear signatures of recent star formation as the dominant source of blue continuum in our complete sample is thus no more than 10-15%. This value is much smaller than the ~ 40% frequency that we found in our previous studies of Seyfert 2 galaxies (e.g., Storchi-Bergmann et al. 2001, Raimann et al. 2003 and references therein).

iii) The four radio galaxies with a significant contribution from young components and/or direct AGN light are all FR II/ x. There seems, therefore, to be a systematic difference between FR I and FR II stellar populations, in the sense that FR II radio galaxies have larger contributions from younger stellar populations. A larger sample is needed to better quantify this difference.

iv) There is an inverse relation between the strength of the emission line [OIII] λ5007 and the mean age of the stellar population, suggesting that younger galaxies have more active nuclei.

v) There is also a relation between the radio power and the mean age of the stellar population in the sense that younger galaxies host more powerful radio sources.

vi) The main difference between the stellar populations of the radio and control sample galaxies is that the former have, on average, a larger contribution from the intermediate 1 Gyr age component. This excess contribution sug-
Figure 10. Histograms for the radio and control sample galaxies, comparing the relative contributions of different age components to the total flux at 4020 Å. Open histograms with a heavy outline show the non-active galaxies while hatched histograms show the radio galaxies.

suggests a relation between the present radio activity and a past episode of star formation which occurred about 1 Gyr ago.

In order to explain the above results we speculate on an evolutionary scenario for the radio galaxies, similar to the one we have proposed for Seyfert galaxies (Storchi-Bergmann et al. 2001): a past event which occurred more than $10^9$ yrs ago (e.g., interaction with a passing external galaxy, or merger) has triggered an episode of star formation in the inner region. After an average delay of $10^8$ yrs the radio activity sets in. Our results also suggest that the more massive the starburst, the stronger the subsequent radio emission.

Comparing the present results for the radio galaxies with those for Seyferts (Storchi-Bergmann et al. 2001), we conclude that while for Seyfert 2 galaxies the delay between the triggering of star formation and the onset of activity would be, on average $10^8$ yr, for the radio galaxies this delay would be an order of magnitude longer.

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