As a result, these studies have shown that the optical properties of radio galaxies, such as radio-loud quasars, are consistent with the predictions of the unified theory. However, the properties of low redshift radio galaxies, such as those observed in the Sloan Digital Sky Survey, are not as well understood. The optical properties of radio galaxies with high redshift are less well understood.

Observations confirm that the unified theory is able to explain the observed properties of radio galaxies. The evidence for the unified theory is consistent with the predictions of the theory, and the observations are consistent with the predictions of the theory. However, there is still much to be done to understand the properties of radio galaxies, and the unified theory is still a work in progress.
gusting that all ellipticals may go through a phase of nuclear activity lasting for a small fraction of the total life of the galaxy.

Few previous observations were devoted to investigation of the dynamical properties of Radio Galaxies (RG). Apart a very small number (11) of radio sources included in the original work on the FP of ellipticals by Faber et al. (1989) (hereafter FA89), only Smith, Heckman & Illingworth (1990; hereafter SHH90) performed a systematic study on the stellar dynamics of Powerful Radio Galaxies (PRG). They compared $<\mu, r_e$, and $\sigma_e$ measurements for a compilation of PRG with the distribution in the FP of the bright ellipticals studied by FA89, concluding that the FP of PRG is consistent with that of normal ellipticals. However they also found evidence for smaller than normal velocity dispersions and significant rotational support in galaxies with marked morphological peculiarity.

In this paper we present a much deeper investigation of the FP of radio galaxies, based on a sample of 73 radio galaxies. The data are in part new (22 objects) and in part collected from the literature (51 objects). Most of literature values were derived from the Hypercat database (Prugniel & Marson 2000). All values of $<\mu, r_e$, and $\sigma_e$ have been processed in order to make them homogeneous to a common standard (see Sec 4.2). Throughout the paper we assume $H_0=50h^{-1}$ km s$^{-1}$ Mpc$^{-1}$ and $q_0=0$.

2. Observations and data analysis

We obtained medium resolution optical spectra of RG selected from the brightest (m$_R<15$) objects in the sample of 79 LzRG previously imaged, in the R filter, by us (Fasano et al. 1996, Govoni et al. 2000a,b). These observations were aimed at deriving the velocity dispersion from stellar absorption lines. In Table 1 we give the list of the objects observed together with exposure times and position angles used for the observations.

Optical spectroscopy was obtained in March/April 1998 and November 1998 with the ESO/Danish 1.52 m telescope at La Silla, using the Danish Faint Object Spectrograph and Camera (DFOSC). We used a CCD Local/Lesser, with 2052 x 2052 pixels combined with an Echelle Grism of 316 grooves/mm yielding a velocity resolution (FWHM) of 71 kms$^{-1}$ (for a slit 1" wide) in the range $\lambda\lambda=4800-5800$ Å. A long slit, 2.0" wide and centered on the galaxy, was oriented along the apparent major axis of the radio galaxy. With this configuration we reach a velocity dispersion resolution $\Delta\sigma=60$ kms$^{-1}$; the scale perpendicular to the dispersion is 0.39/U/pixel. Template reference spectra of standard stars of spectral type from G-S III to K-I-III, with low rotational velocity (V sin(i) $<17$ km s$^{-1}$), were secured at the beginning and at the end of each night. During the observations the seeing ranged between 1.9 and 1.5".

Optical spectra were reduced using standard procedures available in the IRAF package and includes bias subtraction, flat fielding, and wavelength calibration. The accuracy of the latter procedure was checked with measurements of the night sky $\lambda=5577.52$ Å emission line. In all cases a precision of $\Delta V\approx 20$ km s$^{-1}$ was reached. In order to increase the signal to noise and to match the observed spatial resolution (assuming the mean seeing) with the plate scale across dispersion, the spectra were rebinned over three pixels perpendicular to the dispersion, obtaining an effective spatial resolution of 1.17/U/pixel. The observed spectral range includes the $M_{25}$ band ($\lambda\lambda=5175.4$ Å), the E-band (5269 Å) and the FeI line (5335 Å).

The systemic velocity, corrected to the Sun, and the velocity dispersion $\sigma$ were determined using the Fourier Quotient method (Sargent et al. 1977, Bertola et al. 1984). The spectra were first normalized by subtracting the continuum, converted to a logarithmic scale and then multiplied to a cosine bell function that apodizes 10% of the pixels at each end of the spectrum. This forces the ends of the spectra smoothly to zero. Finally the Fourier Transform of the galaxy spectra were divided by the Fourier Transform of a template star whose spectra (late G and early K spectral type) matched that of the galaxy. These spectra are used as templates of zero velocity dispersion.

The best-fit stellar template then yields a profile of the velocity dispersion $\sigma$ and the stellar velocity curve with relative errors for the galaxy. The r.m.s. of the determinations obtained with different template stars turned out to be less than 20 km s$^{-1}$ for $\sigma$ and $\sim 10$ km s$^{-1}$ for the systemic radial velocity $V_r$. The average values of these determinations were adopted as final values of $\sigma$ and $V_r$. 

<table>
<thead>
<tr>
<th>Table 1. Log of the Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>object</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>005-5-016</td>
</tr>
<tr>
<td>013-1-300</td>
</tr>
<tr>
<td>027-3-038</td>
</tr>
<tr>
<td>031-2-343</td>
</tr>
<tr>
<td>032-5-024</td>
</tr>
<tr>
<td>044-9-175</td>
</tr>
<tr>
<td>056-4-329</td>
</tr>
<tr>
<td>058-0-317</td>
</tr>
<tr>
<td>071-3-340</td>
</tr>
<tr>
<td>091-5-119</td>
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<tr>
<td>094-3-034</td>
</tr>
<tr>
<td>104-3-290</td>
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<tr>
<td>110-7-372</td>
</tr>
<tr>
<td>112-3-351</td>
</tr>
<tr>
<td>125-1-122</td>
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<tr>
<td>133-3-337</td>
</tr>
<tr>
<td>140-3-337</td>
</tr>
<tr>
<td>140-4-267</td>
</tr>
<tr>
<td>151-4-072</td>
</tr>
<tr>
<td>152-3-300</td>
</tr>
<tr>
<td>235-5-376</td>
</tr>
<tr>
<td>233-3-327</td>
</tr>
</tbody>
</table>

a) Slit position angle in degrees from North toward East.
Since early-type galaxies exhibit some gradients in the radial velocity and velocity dispersion (Davies et al. 1983, Fisher et al. 1995), the derived 'central' parameter $\sigma_c$ depends on the distances of the galaxies and the size of the aperture used for the observation. In order to compare our velocity dispersions with the data available in the literature we applied aperture corrections according to the procedure given by Jørgensen et al. (1995). The individual measurements of $\sigma$ are therefore corrected to a circular aperture with a metric diameter of $1.19h^{-1}$ kpc, equivalent to $3.4\theta$ at the distance of the Coma cluster.

For 8 of the 22 RGs observed previous determinations of the velocity dispersion were found in the Hypercat database. The comparison between our and previous measurements of $\sigma$ is shown in Figure 1. When more than one measurement of $\sigma$ is present in the literature, we took the mean value quoted by Hypercat. The average difference between our and Hypercat values of $\sigma$ is:

$$<\sigma_{\text{our}} - \sigma_{\text{Hypercat}} > = 4\pm6.4 \text{ km s}^{-1}; \quad \text{r.m.s.} = 18 \text{ km s}^{-1}$$

Additional notes on individual galaxies are given in the Appendix.

Table 2 reports our measurements of $\sigma_c$ and the estimated uncertainties, together with the parameters $<\mu_c>$ and $r_c$, taken from Govoni et al. (2000a), that are relevant to construct the FP. The average surface brightness $<\mu_c>$ has been evaluated from the formula:

$$<\mu_c> = R_T + 5 \log(r_e^2) + 2.5 \log(2\pi),$$

where $R_T$ is the total $R$ apparent magnitude and $r_e^2$ is the effective radius. All these quantities are corrected for the contribution of the point source (see Govoni et al. 2000b), for cosmological dimming and for K-correction according to Poggianti (1997). The distance/systemic velocities used to derive $r_e$ and $<\mu_c>$ are relative to the Cosmic Microwave Background (CMB) reference frame and come from the Lyon Meudon Extragalactic Database (LEDA, Paturel et al. 1997).

3. Extended sample of LzRG

We have collected from the literature stellar velocity dispersion measurements of LzRGs for which photometric and structural parameters are also available. To make these data homogenous with our measurements we processed them applying the same procedure adopted for our subsample of LzRG (see above section and Govoni et al. 2000b).

We excluded from the analysis the radio galaxies belonging to dumbbell systems or close galaxy pairs, as well as those having recession velocity (corrected to CMB) less than 3000 km s$^{-1}$, since these circumstances may induce significant uncertainties in the parameters considered.

3.1. Previous work on the Fundamental Plane of LzRGs

An early investigation of the FP of LzRG was undertaken by FA89 in their study of early-type galaxies. They give $<\mu_c>$ and $r_e$ (in the B band), as well as $\sigma$ for 11 RGs. However 6 objects are dumbbell systems or have small recession velocity and for this reason are not considered in our analysis. For the remaining 5 we obtained $<\mu_c>$ in the R band applying a color correction based on the integrated color (B-R) obtained from Hypercat.

The first systematic study of the FP of RGs was performed by Smith, Heckman & Illingworth (1990, SHI90).
who reported kinematical and photometrical data for 20 powerful radio galaxies previously imaged in the V band (Smith & Heckman 1989, hereafter SH89), as well as for 16 more galaxies from Heckman et al. (1985). Among the latter ones, only 7 are supplied with complete photometric information, whereas 5 objects, out of the remaining 27 in the total sample, turn out to belong to dumbbell systems or close pairs. This reduces the usable sample of SH89 to 22 objects available for FP analysis. In order to derive \( \langle \mu_e \rangle \) consistently with our definitions (see above formula) we used their isophotal magnitudes \( V_{25} \) and the effective radii \( r_e \) reported in SH89 (Table 8) and applied a correction of -0.16 (average difference between \( m_{25} \) and \( m_{24.5} \) in our study of RG; Govoni et al. 2000b) to obtain total magnitudes. Then we corrected for the color term (V-R) using the colors from SH89, when available, or assuming (V-R)=0.55 in the other cases.

### 3.2. Additional data for the Fundamental Plane of LzRG

In order to improve the statistic of our analyses, we have searched the literature for additional LzRG that have measurements of velocity dispersion, \( \langle \mu_e \rangle \) and \( r_e \). We have combined photometric data of LzRGs from the studies of Ledlow & Owen (1995, LO95) and Gonzalez-Serrano & Carballo (2000, GS00) with the velocity dispersions given by Wegner et al. (1999, EFAR) or by Hypercat.

The cross identification between LO95 and EFAR added 17 new LzRGs to our compilation, whereas between GS00 and Hypercat adds 7 more LzRGs. In both cases, in order to derive \( \langle \mu_e \rangle \) consistently with our definitions, we used the magnitudes \( m_{24.5} \) and the effective radii \( r_e \), given in the original papers and applied the same corrections as for the data of SH89.

In total, the sample of LzRG for which we collected data from the literature consists of 51 objects. The relevant data for these objects are given in Tables 3 and 4. These, together with the sample for which we present new data, leads to a total of 73 LzRG, and represents the largest dataset of photometric and spectroscopic data on radio galaxies till now.

### 3.3. Comparison sample of non-radio elliptical galaxies

In order to compare the FP of LzRGs with that of normal galaxies, we used the sample of radio-quiet early-type galaxies studied by Jørgensen et al. (1996, JKF96). It is by far the richest, still homogeneous sample for which both photometric and kinematic information is available. Previous samples of early type galaxies used to describe the FP (e.g. FA89) have a significantly larger scatter with respect to the data of JKF96. Since the JKF96 sample consists of cluster galaxies, it has also the advantage of the reliability of the distance determination.

To use our data on LzRG with the JKF96 data, we converted their Gunn r photometry to the R band, by means of the average relation \( R = r = 0.3 \), given in Jørgensen (1994).

### 4. The Fundamental Plane of radio galaxies

In order to derive the parameters describing the FP:

\[
\log k_{r} = \alpha \log \sigma + \beta \langle \mu_e \rangle - \gamma, \tag{1}
\]

we minimized the root square of the residuals perpendicular to the plane. This procedure is to be preferred with respect to the classical one (minimizing the root square of the residuals along a given axis) when there are measurement errors in all observed quantities. It is also slightly different from that used by JKF96, which minimizes the sum of the absolute residuals perpendicular to the plane.

In Table 5 the FP coefficients \( \alpha \), \( \beta \) and \( \gamma \) obtained using this fitting procedure for different subsamples of radio and non radio galaxies are reported. Since the adopted fitting procedure does not provide analytical form for the uncertainties of the parameters, we indicate in Table 5 the 1σ uncertainties computed according to the classical formalism and assuming the values of the FP coefficients given in the table.

Each sample in the table is indicated with a capital letter and the fits obtained merging together two or more
Fig. 2. The Fundamental Plane of various samples of IzRG (see legend and Table 5) and normal (non radio) ellipticals (JFK96), compared with the best fit (dotted line) to the JFK96 data.

Table 5. The FP in R

<table>
<thead>
<tr>
<th>Sample</th>
<th>$N_{ext}$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>J (JFK96)</td>
<td>22</td>
<td>1.24±0.04</td>
<td>0.330±0.007</td>
<td>8.58±0.06</td>
<td>0.059</td>
</tr>
<tr>
<td>O (This Work)</td>
<td>22</td>
<td>1.36±0.23</td>
<td>0.295±0.031</td>
<td>8.15±0.23</td>
<td>0.071</td>
</tr>
<tr>
<td>L (LO95)</td>
<td>17</td>
<td>1.24±0.23</td>
<td>0.311±0.015</td>
<td>8.21±0.18</td>
<td>0.047</td>
</tr>
<tr>
<td>G (GC00)</td>
<td>7</td>
<td>2.55±0.74</td>
<td>0.311±0.073</td>
<td>11.37±0.53</td>
<td>0.055</td>
</tr>
<tr>
<td>S (SH90)</td>
<td>22</td>
<td>2.60±0.31</td>
<td>0.161±0.021</td>
<td>8.19±0.26</td>
<td>0.070</td>
</tr>
<tr>
<td>F (FA89)</td>
<td>5</td>
<td>2.31±0.48</td>
<td>0.072±0.043</td>
<td>5.86±0.50</td>
<td>0.030</td>
</tr>
<tr>
<td>OLG</td>
<td>46</td>
<td>1.58±0.16</td>
<td>0.310±0.015</td>
<td>8.99±0.15</td>
<td>0.063</td>
</tr>
<tr>
<td>OLGSF</td>
<td>74</td>
<td>1.92±0.15</td>
<td>0.256±0.013</td>
<td>8.69±0.15</td>
<td>0.082</td>
</tr>
<tr>
<td>JOLG</td>
<td>275</td>
<td>1.27±0.04</td>
<td>0.330±0.007</td>
<td>8.56±0.06</td>
<td>0.060</td>
</tr>
<tr>
<td>JOLGSF</td>
<td>303</td>
<td>1.35±0.04</td>
<td>0.308±0.007</td>
<td>8.40±0.06</td>
<td>0.060</td>
</tr>
</tbody>
</table>

Samples are indicated with sequences of letters, according to the previous correspondence (for instance JO means JFK96+This Work).

We note from Table 5 that, in spite of the slightly different fitting procedure, the FP coefficients we found for the JFK96 sample of radio-quiet galaxies (our comparison sample) are indistinguishable from those given in the original JFK96 paper (see their equation [1]). In Figure 2 we plot all the galaxies in the above described samples, together with our FP fit of non radio ellipticals (JFK96).
From Table 5 the FP coefficients derived from our sample of 22 radio-galaxies turn out to be consistent (within 1σ of the estimated uncertainties) with those relative to the control sample of non radio galaxies. The same happens for the 17 radio-galaxies in the LO95 sample. On the contrary, fitting the SHI00 sample of 22 radio-galaxies yields FP coefficients different (well beyond 3σ) from those relative to the comparison sample. This is likely to be due to the presence of a few outliers in their galaxy sample, as shown in Figure 2. Finally, given the small size of FA89 and GC90 samples a reliable estimates of the FP can not be derived from them. Nevertheless, we have reported in Table 5 the coefficients resulting from the formal fit of these samples. In the case of the GC90 sample, they are consistent with those relative to the control sample, whereas considerable differences (again caused by the presence of an outlier) come in the case of the FA89 sample.

In Table 5 we also report the fits obtained merging together two or more galaxy samples. Among them, we assume as representative of the global FP of elliptical galaxies, the fit:

\[
\log r_e^{kpc} = 1.27 \log \sigma + 0.32 \langle \mu_e \rangle_R - 8.56
\]

which includes the comparison sample (JFK96) and the radio samples from this work (O), from LO95 (L) and from GC90 (G). This fit allows to extend the FP up to the bright end of the luminosity function of early-type galaxies.

The M/L ratio is a function of the stellar population and dark matter content of galaxies. In Figure 3 we show the relation between the Mass to Light ratio (M/L) and the velocity dispersion (σ). We derived the masses of our galaxies by using the relation \( M = 5r_e\sigma^2 / G \) (Bender et al, 1992). This figure indicates that IzRGs follow the same relation found for normal elliptical galaxies. The scatter
of the M/L ratio as a function of log $\sigma$ is $\sim 0.2$ dex, similar to that found by JFK96.

5. Conclusions

The main conclusion of this study is that the fundamental plane of radio galaxies, as defined by our collection of data for 73 objects, is consistent with the one defined by normal, non-radio elliptical galaxies. Some recent results on BH demography (Ferrarese & Merritt 2000, Gebhardt et al. 2000) strongly suggest that all galaxies may host a massive BH in the nucleus, and that the BH mass is proportional to the mass of the spheroidal component. This means that, virtually, all ellipticals have the basic ingredient for becoming active. Considering the small amount of gas (few solar masses per year) necessary to sustain the radio emission of even the most powerful radio sources, the activity could be triggered by extremely modest alteration of the status of equilibrium in which galaxies settled soon after they form. According to this view it is therefore not surprising that radio and non radio ellipticals have indistinguishable global properties, irrespective of their nuclear activity. Here, we present one more result supporting this scenario.

Both metallicity effects and age variations have been suggested as the main cause (Faber et al. 1995) of the strong dependence of M/L on $\sigma$, that is on the total mass of the galaxy. This relation is consistent with a progressive reddening of the stellar population going from small to big galaxies (e.g., Prugniel & Simien 1996), but most of dependence remains unexplained. It looks like that ellipticals pass from being baryon dominated to be dark matter dominated with increasing luminosity, with a "fine tuning" required by the small and basically constant dispersion around the FP.

Appendix A: Notes to individual galaxies

0055-016 - UGC 595 - 3C29 this galaxy belongs to the rich cluster A110 and is D26 in the Dressler (1980) list. Smith et al. (1990) measured a velocity dispersion of $199\pm18$ kms$^{-1}$ but recently Wegner et al. (1999) give a value of $253\pm17$ kms$^{-1}$ in better agreement with our measurements.

0131-360 - NGC 612 This galaxy show a strong dust lane along the apparent major axis, our spectrum has been obtained perpendicularly to the dust lane, i.e. along the minor axis of the optical galaxy, no rotation is visible.

0151-115 - 3C218, Hydra A. A well studied galaxy showing strong [OIII]$\lambda = 5007\AA$ emission lines. Heckman et al. (1985) found $\sigma = 308\pm38$ kms$^{-1}$, slightly higher than our measurement $278\pm78$ kms$^{-1}$.

1107-372 - NGC 3557. We measure a velocity dispersion of $295\pm7$ kms$^{-1}$ and a velocity gradient of $\sim 150$ kms$^{-1}$ in the central 5$''$ in good agreement with data available in Hypercat.

1258-321 - ESO443-G024, this galaxy is in the cluster A3537. Dressler et al. (1991) measured a velocity dispersion of $279\pm27$ kms$^{-1}$ in good agreement with our data.

1333-337 - IC 4296. Our value of sigma is lower than the mean value quoted by Hypercat (340 kms$^{-1}$). The agreement is better with the measure of Franx et al. (1989). From our spectrum, taken at PA=60° we measure a rotation of $71$ kms$^{-1}$ in agreement with data taken at the same position angle by Saglia et al. (1993).

1400-337 - NGC 5419. Our measure is in good agreement with the mean value quoted by Hypercat. The spectrum, taken at PA=84°, show a maximum rotational velocity of $-90$ kms$^{-1}$ over 5$''$.

1514+072 - UGC9799, Our measure of the velocity dispersion is very close to the mean value of 247 kms$^{-1}$ quoted in Hypercat.
Dressler, A. Faber, S.M., Burstein, D. 1991, 368, 54
Prugniel, Ph., Simien, F. 1996 A&A 309, 749