Fundamental galaxy parameters for radio-loud AGN and the black hole – radio power connection

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\textbf{ABSTRACT}

We have determined the central velocity dispersions and surface brightness profiles for a sample of powerful radio galaxies in the redshift range $0.06 < z < 0.31$, which were selected on the basis of their young radio source. The optical hosts follow the fundamental plane of elliptical galaxies, showing that young radio sources reside in normal ellipticals, as do other types of radio galaxies into which these objects are believed to evolve. As young radio sources are relatively straightforward to select and the contributions of the AGN light to the optical spectra are minimal, these objects can readily be used to study the evolution of the fundamental plane of elliptical galaxies out to $z=1$, independently of optical selection effects.

The black hole masses, $M_{bh}$, of the objects in our sample have been determined using the tight empirical relation of $M_{bh}$ with central velocity dispersion, $\sigma_e$, and for literature samples of classical radio galaxies and optically selected ellipticals. Only the optically selected in-active galaxies are found to exhibit a correlation between $M_{bh}$ and radio luminosity. In contrast, the radio powers of the AGN in the samples do not correlate with $M_{bh}$ at all, with objects at a given black hole mass ranging over 7 orders of magnitude in radio power.

We have been able to tie in the local population of powerful radio sources with its parent population of in-active elliptical galaxies: the local black hole mass function has been determined using the elliptical galaxy luminosity function and the Faber-Jackson and $M_{bh} - \sigma$ relations. This was combined with the fraction of radio-loud black holes as function of $M_{bh}$, as determined from the optically selected galaxy sample, to derive the local volume-density of radio galaxies and the distribution of their black hole masses. These are shown to be consistent with the local radio luminosity function and the distribution of black hole masses as found in the radio selected samples, and confirms that elliptical galaxies comprise the large majority of the radio-loud population of active galaxies.

\textbf{Key words:} galaxies:active – galaxies:evolution – galaxies:fundamental parameters

1 INTRODUCTION

1.1 Galaxy formation and the fundamental plane

How and when galaxies were formed and how they have evolved since, is one of the central issues of contemporary astrophysics today. Elliptical galaxies may be the best objects to study galaxy evolution, since their optical light is not dominated by relatively recent star-formation, unlike that of spiral galaxies, and their observational properties are a better reflection of their long-timescale cosmological development.

In the 1980s it was shown that the main global properties of local elliptical galaxies, velocity dispersion, surface brightness and effective radius, are strongly correlated, and that they describe a plane in this 3-dimensional parameter space (Dressler et al., 1987; Djorgovski & Davis, 1987). Initially, this ‘fundamental plane’ (FP) of elliptical galaxies drew attention mainly for its use as a distant indicator, to measure the Hubble constant and peculiar motions in the local universe. However, it was also realised that it implied a strong regularity in the process of galaxy formation, in particular that the mass-to-light (M/L) ratio varied only
slightly over 4 orders of magnitude in galactic mass (Djorgovski & Davis, 1987).

Since the M/L ratio is a strong function of the age of the stellar population, the study of the fundamental plane as function of redshift is a sensitive diagnostic of the evolutionary history of galaxies. van Dokkum, Franz and Kelson and collaborators, who observed elliptical cluster galaxies with the Keck telescope and the HST, located at z=0.39 (van Dokkum & Franx 1996), z=0.58 (Kelson et al. 1997), and z=0.83 (van Dokkum et al. 1998), showed that the M/L ratio evolves as $\Delta \log M/L_B \propto -0.4z$ ($\Omega_m = 0.3, \Omega_\Lambda = 0$), putting strong constraints on the formation epoch of cluster ellipticals, with $z_{\text{form}} > 2.8$ for a Salpeter initial mass function.

The Mg b or Mg$_2$ indices are also valuable measures of the age of the stellar population, which is often used in conjunction with the FP. The Mg$_2$ index is found to be correlated with the central velocity dispersion in local elliptical galaxies, with only a small scatter (eg. Dressler et al., 1987; Djorgovski & Davis, 1987; Jorgensen, Franx & Kjaergaard 1996). Ziegler & Bender (1997) showed that for cluster galaxies at $z=0.37$, this correlation is offset by $\langle \text{Mg b}\rangle \approx -0.4\AA$ which can be fully attributed to the lower luminosity-weighted ages of these stellar populations at this earlier epoch.

These studies may seem to suggest that, except for perhaps some minor details, the evolution of elliptical galaxies is well understood. However, various strong biases may still be present in the studies described above. The most serious bias may be the progenitor bias (van Dokkum & Franx 1996): present day ellipticals which were spirals at an earlier epoch, would not have been included in a sample at that epoch, biasing the sample to what are likely to be the oldest galaxies. Furthermore, there is also an environmental bias: present studies are focused on cluster galaxies, while it is not known how these clusters evolve with cosmological epoch. For example, it is far from clear what a local cluster such as Coma would have looked like at high redshift, and to what present-day structures the high-z clusters have evolved into. More generally, connecting populations at one redshift with their predecessor at high redshift, without making uncertain assumptions about the history of star formation is a problem.

1.2 The role of nuclear activity in galaxy formation and evolution

The place of active galaxies in the general picture of galaxy evolution is unclear. Until recently, AGN were seen as rare and peculiar objects, which, although interesting for their own sake, were disconnected from galaxy evolution issues. However, the recent discovery that every galaxy seems to have a central massive black hole, the mass of which is closely related to the total mass of (the bulges of) its host (Magorrian et al, 1998; Gebhardt et al. 2000), has changed this perception dramatically. It is now clear that the formation and evolution of the central massive black hole is closely linked to that of the host galaxy (eg. Silk & Rees 1998). In addition, it implies that all galaxies may be capable of having phases of central activity, meaning that active galaxies are just normal galaxies, with their central black hole coincidently caught during a period of (high) accretion. This places active galaxies back in the centre of attention of galaxy formation and evolution studies, especially since they are relatively easy to select at high redshift. Recent claims suggest that non-thermal radio emission from ellipticals is strongly correlated with the mass of their central black hole, ranging from dwarf ellipticals to powerful radio galaxies (Franceschini et al. 1998). This would make the connection between quiescent and active galaxies even stronger.

1.3 Radio galaxies as probes of galaxy evolution

Since active galaxies play such a potentially important role in galaxy evolution, it is important to determine their fundamental structural parameters as function of redshift. An additional factor is that selection of AGN allows the study of galaxy evolution independently of the optical selection biases as mentioned above. Smith, Heckman & Illingworth (1990) have studied the fundamental plane parameters of nearby powerful radio galaxies, and showed that they indeed reside in normal ellipticals. A similar result has been found recently by Bettoni et al. (2002). Unfortunately, it is almost impossible to use similar objects at higher redshift, since their spectral energy distributions have invariably been found to be strongly influenced by AGN light, especially in the optical (eg. optical/UV alignment effect, McCarthy et al. 1987, Chambers et al. 1987).

This problem can be avoided by selecting galaxies containing a very young radio source. In the very early stages of radio source evolution, when the radio source is only 100-1000 years old and confined to the central hundred parsecs, the contribution of the AGN to the global properties of its host galaxy is still minimal (Snellen et al. 1996a,b; 1999). Broadband photometry showed that their optical to near-infrared colours are consistent with passively evolving ellipticals, indicating that their light is dominated by old stellar populations. The dispersion in their $R$ and $K$ band Hubble diagrams (0.3 mags) is smaller than that for other classes of radio galaxies, indicating a homogeneous and well behaved population of hosts (Snellen et al. 1996a,b). In addition, their optical spectra typically only show weak emission lines but deep stellar absorption lines, again indicative of them being dominated by old stellar populations (Snellen et al. 1999). For example, the archetype young radio source, B0108+388, is as powerful as Cygnus A. However, it has a remarkably low OIII$_{5007}$ equivalent width of only $\sim$4Å (Lawrence et al. 1996), corresponding to a line luminosity about a factor 50 lower than that of Cygnus A.

That the contamination from young radio-loud AGN is only small or even absent may not come as a surprise. The young radio source may not yet have pierced through the dense and dusty central regions of the host. AGN related light is also likely to still be confined to the inner hundreds of light years, and obscured from our view. There is indeed much evidence through HI absorption studies of young radio-loud AGN that large column densities of gas are present (eg. Carilli et al. 1999; Peck, Taylor & Conway 1999).

In this paper, we investigate the use of the host galaxies of young radio-loud AGN as probes of galaxy evolution. The connection between radio activity and black hole mass, as inferred from their central velocity dispersion, has also been
investigated. We present high dispersion spectroscopic and optical CCD imaging data of a sample of 7 young radio-loud AGN located between 0.06 < z < 0.31. Section 2 describes the properties of young radio-loud AGN and the selection of the sample. Section 3 describes the observations, reduction and analysis. Section 4 and 5 present the results and discussion. For consistency with previous papers on this subject, we use a cosmology with \( H_0 = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 1.0 \), \( \Omega_{\Lambda} = 0 \), throughout this paper, unless stated otherwise.

2 YOUNG RADIO-LOUD AGN AND THE SELECTION OF THE SAMPLE

2.1 Characteristics of young radio-loud AGN

In the course of the last decade, a class of extragalactic radio source has been identified as being very young. This has opened many unique opportunities for radio source evolution studies. Unfortunately, the nomenclature and use of acronyms in this field of research is rather confusing. This is mainly caused by the different ways in which young radio-loud AGN are selected. Selections of young sources are made in two ways, the first based on their broadband radio spectra, and the second based on their compact morphology. A convex shaped spectrum, peaking at about 1 GHz distinguishes young radio sources from other classes of compact radio sources. In this case they are called Gigahertz Peaked Spectrum (GPS) radio sources (eg. O’Dea et al. 1991, O’Dea 1998). Similar objects, which are typically an order of magnitude larger in size, have their spectral turnovers shifted to the 10 – 100 MHz regime, causing them to be dominated at cm wavelengths by the optically thin parts of their spectra. These are called Compact Steep Spectrum (CSS) radio sources to distinguish them from the general population of extended steep spectrum sources (eg. Fanti et al. 1990).

On the other hand, young radio sources are found in multi-frequency VLBI surveys, in which they can be recognised by compact jet/lobe-like structures on both sides of their central core. They are called Compact Symmetric Objects (CSO, Wilkinson et al. 1994). Their double sided structures clearly distinguish them from the large majority of compact sources showing one-sided core-jet morphologies. Larger versions of CSOs are subsequently called Medium Symmetric Objects (MSO) and Large Symmetric Objects (LSO).

The overlap between the classes of CSO and GPS galaxies is large and we believe that they can be considered to be identical objects. However, a substantial fraction of GPS sources are optically identified with high redshift quasars, which in general show core-jet structures (Stanghellini et al. 1997). The relationship between GPS quasars and GPS/CSO galaxies is not clear (Snellen et al. 1998b), and the former may not be young objects at all.

Although it was always speculated that GPS sources were young objects, only recently has strong evidence been found to support this hypothesis. Monitoring several prototype GPS/CSO sources over a decade or more using VLBI, allowed Owstianik & Conway (1998) and Owstianik, Conway & Polatidis (1998) to measure their hotspot advance speeds to be \( \sim 0.1h^{-1}c \). These imply dynamical ages of typically \( 10^2-3 \) years. Similar studies with similar results have now also been conducted by Tschager et al. (2000) and Taylor et al. (2000). Additional proof for youth comes from analysis of the overall radio spectra of the somewhat larger CSS sources. Murgia et al (1999) show that their spectra can be fitted with synchrotron ageing models, implying ages of typically \( 10^{3-5} \) years.

The work of these authors indicate that GPS/CSO sources are very young and the likely progenitors of large, extended radio sources. However, there may also be a population of young radio-loud AGN which are just short-lived, and do not evolve into large size radio sources (Readhead et al. 1994; Alexander 2000). In the latter case, the connection of these host galaxies with those of other types of AGN would be less clear.

2.2 Sample selection

The sample of young radio sources used in this paper is based on the sample of bright GPS sources of Stanghellini et al. (1998). This complete sample of 33 objects contains sources with turnover frequencies between 0.4 and 6 GHz, with \( S_5 > 1 \text{ Jy} \), and are located at \( \delta > -25^\circ \) and galactic latitude \( |b| > 15^\circ \). Of this sample, 19 are optically identified with galaxies, of which 6 are found at \( z < 0.31 \). Two objects, B1345+125 and B1404+286, were omitted from the sample, since these were known to exhibit broad Seyfert-type emission lines in their optical spectra, implying a strong contribution of AGN related light. We further excluded B0428+205 due to its low galactic latitude and high foreground extinction.

To enlarge the usable sample and to be able to investigate possible correlations between host galaxy properties or optical AGN contribution and radio power, we included nearby GPS galaxies from the sample of Snellen et al. (1995) at intermediate flux densities, and from Snellen et al. (1998a) at faint flux densities. This involved the only GPS galaxy at low redshift from the intermediate sample, B1144+3517, and two nearby galaxies from the faint GPS sample, B0830+5813 and B1946+7048. Details of the young radio-loud AGN are given in table 1. Column 1 gives the B1950 name, and column 2 gives the J2000 position. Column 3 gives the redshift. Column 4 gives the R band magnitude, taken from Snellen et al. (1996a), O’Dea et al. (1996) and Snellen et al. (1998b). These are approximately corrected to the Cousins filter system, and galactic foreground extinction is taken into account, which is given in column 5 (Schlegel et al. 1998). Their 5 GHz radio power, radio peak frequency, peak flux density, angular and projected linear size are given in columns 6 to 10.

3 OBSERVATIONS, DATA REDUCTION AND ANALYSIS

The observations for this project are divided into three parts. 1) High-dispersion spectroscopy, to determine the velocity dispersions and absorption line strengths of the objects. 2) Deep I-band CCD imaging to determine the surface profiles of the objects, and 3) B, V and R-band observations to determine the rest-frame B-band effective surface densities of these galaxies.
Figure 1. The part of the spectra used to measure the velocity dispersion, shown in order of increasing redshift. The thick lines show the best fit to the velocity broadened stellar spectra. Note that in some cases, e.g. for B0941-0805, the [NI]5199Å emission line had to be removed before the fitting procedure.

Figure 2. The normalised galaxy profiles with their best fits. The profile of B0830+5813 is found to flatten in the central part.
Table 1. Details of the young radio-loud AGN in the sample.

| B1950 Name | Position (J2000) | z   | R  | E_R  | P_{5GHz} | ν_{peak} | S_{peak} | θ  | Size |
|------------|------------------|-----|----|-----|----------|----------|----------|----|------|
| B0019−0001 | 00 22 25.5 +00 14 56 | 0.306 | 18.1 | 0.071 | 26.7 | 0.8 | 3.5 | 70 | 390 |
| B0830+5813 | 08 34 11.1 +58 03 21 | 0.094 | 15.9 | 0.231 | 24.1 | 1.6 | 0.07 | <5 | <12 |
| B0941−0805 | 09 43 36.9 −08 19 31 | 0.227 | 17.5 | 0.076 | 26.4 | 0.5 | 3.4 | 50 | 231 |
| B1144+3517 | 11 47 22.1 +35 03 01 | 0.063 | 14.0 | 0.054 | 25.1 | 2.4 | 0.7 | 40 | 66  |
| B1819+6707 | 18 19 44.4 +67 08 47 | 0.221 | 17.7 | 0.109 | 25.5 | 0.8 | 0.3 | 19 | 86  |
| B1946+7048 | 19 45 53.5 +70 55 49 | 0.101 | 16.3 | 0.526 | 25.4 | 1.8 | 0.9 | 32 | 80  |
| B2352+4933 | 23 55 09.4 +49 50 08 | 0.238 | 18.2 | 0.484 | 26.5 | 0.7 | 2.9 | 70 | 333 |

Figure 3. The galaxy spectra of which the velocity broadened K-star spectra are subtracted. The three adjacent panels to the right zoom in on the [OIII]4959Å, [OII]5007Å, and the [NI]5199Å emission lines, with the dashed lines indicating their rest-frame wavelengths, assuming the absorption line redshifts.

3.1 High-dispersion Spectroscopy

The spectroscopic observations were carried out using the 4.2-m William Herschel Telescope (WHT) located at the Roque de Los Muchachos Observatory, La Palma in Spain. Observations were carried out during two observing sessions July 29/30, 1997 and November 9-11, 1998. Both observing runs were under non-photometric and variable seeing conditions. Table 2 gives the log of the observations, with in column 1 the object name, and column 2 the observing run(s) during which the source was observed (1=July ’97, 2=Nov ‘98). The exposure times per source ranged from 30 minutes to several hours, dependent on the redshift of the target and weather (a significant proportion of the observing time was affected by clouds).

The red arm of the ISIS long-slit spectrograph was used, with the R600R grating, which has 600 grooves/mm. The spectra were centred on the redshifted Mg b absorption feature near 5170Å. The approximate central wavelengths are given in column 3 of table 2. The detector used was a Tektronic 1024 × 1024 CCD, which resulted in a dispersion of 0.79 Å per pixel, and a spatial resolution of 0.3 arcseconds. For all observations a slit-width of 1.0 arcseconds was used. The spectral resolution for this setup was determined to be 1.6 Å FWHM. The rest-frame spectral resolution for the observations of each target is given in column 4 of table 2. The resulting signal-to-noise ratio per pixel is given in column 6.

Reduction and calibration of the spectra

The data were reduced in IRAF. The individual raw images were first bias subtracted. After each target, an exposure was taken of the Tungsten lamp with the telescope pointing in the same position. This was normalised and cor-
Table 2. Parameters of the WHT spectroscopic observations

| B1950 Name | Obs. run | Obs. wave | $\sigma_{\text{sys}}$ | SNR pix$^{-1}$ |
|------------|----------|-----------|----------------------|----------------|
| B0019−0001 | 1&2      | 6800      | 30                   | 15             |
| B0830+5813 | 2        | 5650      | 36                   | 19             |
| B0941−0805 | 2        | 6350      | 32                   | 13             |
| B1144+3517 | 1        | 5500      | 37                   | 35             |
| B1819+6707 | 1        | 6350      | 32                   | 26             |
| B1946+7048 | 1&2      | 5700      | 35                   | 12             |
| B2352+4933 | 1        | 6450      | 32                   | 16             |

The wavelength calibration was performed using a CuAr calibration lamp. The wavelengths of the main skylines in the non-background subtracted images were checked, and if necessary, a small shift in wavelength was applied. Finally, the spectra were corrected to the heliocentric standard. The uncertainty in the absolute wavelength calibration is estimated to be 0.2Å (~10 km/sec).

The velocity dispersions and absorption-line redshifts

The spectra were analysed by a Fourier Quotient method (Simkin 1974; Sargent et al. 1977), using the software package IDL. To determine the velocity dispersion and the absorption line redshifts of the galaxies, their spectra were compared to that of K-stars. These stars proved to provide the most appropriate absorption line spectra for comparison to these old elliptical galaxies. For each galaxy, the continuum was subtracted using a 5th order polynomial, after which the extremities of the spectrum were tapered using a Cosine-bell function. The Fourier transform of this spectrum was divided by that of the continuum subtracted and tapered star spectrum. The result represents the broadening function which was fitted by a Gaussian, and gives the redshift, velocity dispersion, and relative strength of the absorption lines of the galaxy to that of the template star. This fitting in Fourier space was typically performed over a wave number range corresponding to 3-100Å. Variations in redshift and velocity dispersion between different template stars were found to be minimal. In some cases the procedure was preceded by the removal of a small contribution from the [NI]5199Å emission line.

Since elliptical galaxies exhibit radial gradients in their velocity dispersions, the measured velocity dispersion had to be corrected for the effective aperture size of the observations. We used the relation found by Jorgensen, Franx & Kjærgaard (1995) to correct the velocity dispersions to an aperture diameter of 1/4 of the effective radius, $r_e/4$. This resulted in aperture corrections up to 20 km sec$^{-1}$.

$Mg b$ absorption line equivalent widths

The strength of the Mg$b$ absorption feature was measured in an ‘index passband’ flanked by two ‘pseudo-continua’ (see Worthey 1994). The wavelength-ranges of the index and continuum band are as defined in Worthey et al. (1994, table 1). Unfortunately, due to a varying contribution of the [NI]5199Å emission line in the upper pseudo-continuum band of the Mg$b$ index, the standard Mg$b$ bands could not be used. Instead, an upper pseudo-continuum band at 5205−5220Å was used, avoiding this line. Our template star spectra were used to calibrate this new measure of the Mg$b$ index, and we found the empirical relation $Mg b=0.677 + 0.790 \times Mg b_{\text{alt}}$, to correct these values.

The measured absorption indices had to be corrected for the velocity broadening of the spectra. This effect smears out the absorption lines, possibly extending them to outside the index passband and into the pseudo-continuum bands, resulting in a reduction of the measured absorption index. This effect, which is a function of the velocity dispersion, is corrected for by estimating its influence by velocity broadening the stellar-spectra. The corrections, in the order of 10%, were compared to that derived by Trager et al. (1998), and found to be similar.

Since elliptical galaxies have radial gradients in line strengths, the effects of different aperture size must also be taken into account. We used a similar approach to that of Ziegler & Bender (1997), using Mg$b$ profiles analysed by Gonzales & Gorgas (1995). The values were corrected to a radius of $r_e/4$, resulting in an adjustment between −0.25 and +0.28.

The emission line equivalent widths and redshifts

The best fitting velocity broadened stellar spectrum was subtracted from each galaxy to isolate the emission lines and measure their equivalent widths. The velocity shifts of the emission lines were determined by comparing the measured peak wavelengths with that of laboratory rest-frame measurements.

3.2 I-band CCD imaging

The imaging observations to measure the effective radii of the galaxies were also carried out using the WHT, this during the second observing session at November 9-11, 1998. The weather was non-photometric and the seeing conditions varied considerably. The auxiliary port camera at the Cassegrain focus was used with a Tektronics 1024×1024 CCD detector, which resulted in a 0.11′′ pixelsize and an unvignetted (circular) field with a diameter of 1.8′. After every exposure of a few minutes, the telescope was offsetted by tens of arcseconds, to allow more accurate sky-subtraction. Total exposure times ranged from 10 to 45 minutes per galaxy.

The data were reduced in IRAF. The individual raw images were first bias subtracted and flat fielded. These were then combined using median filtering to produce a fringe-images which was then appropriately normalised and subtracted from the frames. The centroids of bright stars on the frames were used to determine their relative shifts, which
were then combined to produce the final image. No flux calibration was attempted due to the non-photometric conditions.

The effective radii

The reduced I band images were used to determine the effective radii of the galaxies. This analysis was done in the IDL software package. Firstly, the centroid of a galaxy was determined and its ellipticity fitted at an isophote at 20% of the value of the central peak. The level of intensity was measured for an increasing major axis, using the whole area of the value of the central peak. The level of intensity was determined and its ellipticity fitted at an isophote at 20% of the central peak. The effective radii in rest-frame B. Observations were carried out during an observing session from June 14 to June 23 2001, and during service observations on July 4 and August 19 2001. All JKT observations were under good photometric conditions, and typical seeing of 1–1.5″. We used the CCD camera with the default SITE2 detector, which has 2048×2048 24μm pixels, resulting in an image scale of 0.33 arcsec/pixel. We observed the objects in B and V, or in V and R filter (depending on the redshift) for 2×300 sec in each filter. Standard star fields from Jorgensen (1994) were observed throughout the nights at several zenith distances.

The data were reduced in a standard way, in a similar way as the WHT I-band data. The photometric zero-points were found to vary by less than 0.1 magnitude between the different observing nights.

Rest-frame B-band effective surface brightness

To determine the effective surface brightness, $I_e$ in rest-frame B band, first the effective surface brightnesses were measured in each filter: the ellipticity and position angle of the galaxies as determined from the deep I-band observations were used to determine the surface brightness as function of radius for each galaxy, excluding some areas containing neighbouring objects. This 1D profile was then fitted with an $r^{1/4}$ law, using the effective radii as found from the I-band observations, allowing $I_e$ and the sky-level to vary. As a consistency check, the total intensities of the galaxies were also measured, using a large aperture of $>> r_e$. For a perfect 2-dimensional De Vaucouleur profile, these relate as $I_{tot} = 22.66 I_e r_e^2$. For the galaxies free of nearby objects, they were found to match within 0.1 magnitude.

The $V$ and $R$ band flux density scales were corrected to match the B band zero-points, adopting an absolute spectral irradiance for a zero magnitude object of $6.61 \times 10^{-9}$, $3.64 \times 10^{-9}$ and $2.25 \times 10^{-9}$ erg cm$^{-2}$ sec$^{-1}$ Å$^{-1}$ in the $B$, $V$ and $R$ band respectively, and were also corrected for galactic foreground extinction using the values of Schlegel et al. (1998). Interpolation between the surface brightnesses in the different filters was used to obtain the rest-frame B-band surface brightness. This was then corrected for the cosmological dimming and bandpass effects of $(1+z)^5$.

For two galaxies, B0830+5813, and B0914-0805, only R band images were available. For these we applied a K-correction, derived from the broadband colours of the other galaxies in the sample.

### 3.3 B,V and R-band CCD imaging

Short CCD exposures of the objects were taken with the Jacobus Kapteyn Telescope, which is also located at the the Roque de Los Muchachos Observatory, La Palma in Spain. These served to determine their surface brightnesses at their effective radii in rest-frame B. Observations were carried out during an observing session from June 14 to June 23 2001, and during service observations on July 4 and August 19 2001. All JKT observations were under good photometric conditions, and typical seeing of 1–1.5″. We used the CCD camera with the default SITE2 detector, which has 2048×2048 24μm pixels, resulting in an image scale of 0.33 arcsec/pixel. We observed the objects in B and V, or in V and R filter (depending on the redshift) for 2×300 sec in each filter. Standard star fields from Jorgensen (1994) were observed throughout the nights at several zenith distances.

The data were reduced in a standard way, in a similar way as the WHT I-band data. The photometric zero-points were found to vary by less than 0.1 magnitude between the different observing nights.

### 4 RESULTS AND DISCUSSION

The results of the imaging and spectroscopy are given in table 3. Column 1 gives the B1950 name, columns 2 and 3 give the redshift and the velocity dispersions respectively. Columns 7 and 8 give the rest-frame equivalent widths for [OIII]5007Å emission line. Column 9 gives the velocity shift of the [OIII] line with respect to absorption line redshift, where a positive value indicates a redshift. The uncertainties in $I_e$ are typically 0.05 magnitude, while the uncertainties in the equivalent widths are $\sim$ 10%.

The part of the spectra used to measure the velocity dispersions of the galaxies is shown in figure 1, in order of increasing redshift. The thick lines indicate the best fit to the velocity broadened K-star spectra. The measured velocity dispersions range from from 146 km sec$^{-1}$ for B0830+5813, to 228 km sec$^{-1}$ for B0019-000. Figure 2 show the normalised galaxy profiles with their best fits. The observed effective radii range from 1.1″ for B009−0001, to 11.9″ for B0830+5813. Note that the profile of B0830+5813 slightly flattens in its inner part. The best fitted velocity broadened...
The main aim of the project was to investigate whether young radio-loud AGN could be used to study the cosmological evolution of the fundamental plane for ellipticals, being selected independently of optical selection biases. Figure 4 shows the fundamental plane with the angle of projection in the $\sigma, I_e, r_e$ space chosen to be similar to that used in previous studies, with on the horizontal axis the logarithm of the effective radius, $r_e$ (in kpc), and on the vertical axis 1.2 times the logarithm of the velocity dispersion $\sigma$ (in km sec$^{-1}$) minus 0.83 times the logarithm of the brightness level at the effective radius, $I_e$, with $I_e = 10^{-0.4} \mu e$. The data are

K-star spectra were subtracted from those of the galaxies to obtain their emission line spectra. These are shown in figure 3. The three adjacent panels to the right zoom in on the [OIII]4959Å, [OIII]5007Å, and the [NI]5199Å emission lines, with the dashed lines indicating their rest-frame wavelengths, assuming the absorption line redshifts. It shows that the emission line redshifts correspond well with those inferred from the absorption lines, except for B2352+4933, which emission lines are clearly redshifted by 350 km/sec.

4.1 The Fundamental Plane

The main aim of the project was to investigate whether young radio-loud AGN could be used to study the cosmological evolution of the fundamental plane for ellipticals, being selected independently of optical selection biases. Figure 4 shows the fundamental plane with the angle of projection in the $\sigma, I_e, r_e$ space chosen to be similar to that used in previous studies, with on the horizontal axis the logarithm of the effective radius, $r_e$ (in kpc), and on the vertical axis 1.2 times the logarithm of the velocity dispersion $\sigma$ (in km sec$^{-1}$) minus 0.83 times the logarithm of the brightness level at the effective radius, $I_e$, with $I_e = 10^{-0.4} \mu e$. The data are

K-star spectra were subtracted from those of the galaxies to obtain their emission line spectra. These are shown in figure 3. The three adjacent panels to the right zoom in on the [OIII]4959Å, [OIII]5007Å, and the [NI]5199Å emission lines, with the dashed lines indicating their rest-frame wavelengths, assuming the absorption line redshifts. It shows that the emission line redshifts correspond well with those inferred from the absorption lines, except for B2352+4933, which emission lines are clearly redshifted by 350 km/sec.

Figure 4. The fundamental plane of the host galaxies of young radio-loud AGN (solid squares), with on the horizontal axis their effective radii, and on the vertical axis a combination of the velocity dispersion and their effective brightness, corrected for the cosmological evolution in the mass-to-light ratio as found by van Dokkum et al. (1998). The solid line indicates the fundamental plane of elliptical galaxies, as derived from nearby galaxies by Faber et al. (1989; small circles). The diamonds are the radio galaxies measured by Smith et al. (1990).

Figure 5. The offset of the host galaxies to the local fundamental plane for cluster ellipticals as function of redshift. The dotted line is the evolution in mass-to-light ratio as found by van Dokkum et al. (1998). The symbols are as in figure 4. There is a possible hint that the more distant galaxies are brighter, but more data are needed to confirm this.
corrected for the cosmological evolution in mass-to-light ratio as found by van Dokkum et al. (1998), corresponding to \( \Delta \text{mag} = 1.22 \times z \). The solid squares show the galaxies in the sample, and the diamonds are the radio galaxies from Smith, Heckman & Illingworth (1990). The small circles are the local ellipticals from Faber et al. (1989) with heliocentric velocities >1500 km/sec, with the solid line their best linear fit. The galaxies in our sample follow the fundamental plane well, with an average offset of 0.01 and a dispersion of 0.17, similar to that of the Smith et al. sample, but with a slightly higher dispersion than the local galaxies in the Faber et al. sample (0.13).

To investigate whether evolution in M/L is visible over the small redshift range in our sample, the offsets of the datapoints to the local fundamental plane, \( \Delta \text{FP} \), as function of redshift is shown in figure 5. The symbols are as in figure 4, with the grey band indicating the dispersion in the local fundamental plane, and the dashed line showing the evolution as found by van Dokkum et al. (1998) for cluster ellipticals. The galaxies containing young radio sources located at \( z>0.2 \) seem to have on average a slightly positive offset from the local fundamental plane, with \( \Delta \text{FP}=0.10 \pm 0.06 \). Therefore evolution is only detected at a 1.7\( \sigma \) level in this small dataset. Clearly, more data are needed, preferably out to higher redshift, to confirm evolution, and to test the findings by van Dokkum et al.

### 4.2 The Mg b - \( \sigma \) relation

The absorption line strengths of a galaxy also give a good, independent insight in its stellar population. The Mg b-\( \sigma \) relation, and its dependence on redshift, has been shown to be a powerful tool to study galaxy evolution (Ziegler & Bender 1997). The Mg b-\( \sigma \) relation for the galaxies in our sample is shown in figure 6. The small circles are the data from the local Faber et al. sample, where the best fit is indicated by the solid line. These datapoints were converted Mg\(_2\) magnitudes, using the relation \( \text{Mg b}\_\lambda 5175 = 15.0 \text{Mg}_2 \) (Ziegler & Bender 1997). The Mg b index of B0941-0805 is clearly lower than expected from the local relation. Since this object exhibit a strong emission line spectrum, we suspect that this Mg b deficit is caused by a contamination of the continuum by AGN related light. In figure 7, the offsets of the Mg b indices to the local Mg b-\( \sigma \) relation is shown to be clearly correlated with \( \text{OIII}\_5007 \) equivalent width, indicating that AGN contamination indeed plays a role. The Mg b deficit in B0941-0805 can be explained by an AGN continuum contribution of 35\%. For the other galaxies in the sample the AGN contribution is less than <5-10\%. Note that this AGN contamination is for nuclear spectra, using a narrow slit. It is unlikely to have any effect on the determinations of the surface brightness profiles as done at and beyond \( r_e \), and it is therefore improbable to affect the determination of the fundamental plane parameters. However, this AGN contribution, although generally small, makes investigating galaxy evolution using the Mg b-\( \sigma \) relation not very useful for radio galaxies.

### 4.3 Black hole masses and their connection with radio power

The work by Gebhardt et al. (2000) and Ferrarese & Merrit (2000) have shown that the mass of a central black hole is strongly correlated with the central velocity dispersion of its host galaxy. According to Gebhardt et al. the relation follows

\[
M_{bh} = 1.2 \times 10^8 \times \left( \frac{\sigma}{200 \text{ km/s}} \right)^{3.75} M_\odot
\]

which is found to have a lower dispersion than the correlation with absolute (bulge) magnitude. This \( M_{bh} - \sigma \) relation allows us to infer black hole masses from the central velocity dispersion measurements, for the galaxies in our sample, and those in Smith et al. and Faber et al. Uncertainties in the black holes masses are dominated by the scatter in the \( M_{bh} - \sigma \) relation, which is estimated to be a factor of \( \sim 2 \) (Gebhardt et al. 2000).

A variety of authors have discussed the relation between \( M_{bh} \) and radio power. Long before the correlations between black hole mass and central velocity dispersion or galactic
Figure 8. The radio luminosity at 1.4 GHz versus black hole mass, as derived from the central velocity dispersion. The squares are those objects selected in the radio (from this paper and Smith et al. 1990). The open and closed circles are optically selected galaxies from the Faber et al. (1989) sample, with the former being point sources in the NVSS, and assumed to be radio-quiet, and the latter being extended in the NVSS and assumed to be radio-loud AGN. The few diamonds at low black hole mass are galaxies added from the local group. The solid line is the $M_{\text{bh}} - P_{\text{radio}}$ relation as found by Franceschini et al. (1998).

To investigate these issues further, and in particular the relative position of radio galaxies on the $M_{\text{bh}} - L_R$ relation, we correlated the galaxies from Faber et al. with the NVSS-VLA 1.4 GHz survey (Condon et al. 1998) and determined their radio luminosities and sizes.

The $M_{\text{bh}} - L_R$ relation for the galaxies in the Faber et al. (circles), and the radio selected galaxies from Smith et al. and this paper (squares) are shown in figure 8. The galaxies in Faber et al. which exhibit extended radio structure, and therefore clearly identified as active galaxies, are indicated by solid circles. A few objects from the local group are added, and are indicated by diamonds.

To avoid the diagram being crowded by meaningless upperlimits, only those objects are plotted, if their radio flux would have been detectable in the NVSS if they radiate at a luminosity expected from the Franceschini relation. Although this produces a varying redshift cut-off with black hole mass, it does not bias the result towards particular radio luminosities. Clearly, the radio luminosities of the presumably inactive galaxies correlate well with black hole mass, although they seem to be slightly fainter than expected from the Franceschini relation, and have a larger scatter, with the radio power of inactive galaxies at a given black hole mass ranging more than 2 orders of magnitude. The active galaxies (those selected in the radio, and those selected from the Faber et al. sample exhibiting extended NVSS emission), do not show any sign of a correlation with black hole mass. At a given $M_{\text{bh}}$, the radio luminosity can span over 7 orders of magnitude, making radio power unsuitable as a black hole mass estimator. We note that the
black hole masses for radio galaxies as derived by Dunlop et al. (2002) are on average about a factor of 4 higher than given here (assuming $M_{bh}=0.0013 M_{bulge}$). This is caused by their different method used to determine $M_{bh}$, based on the bulge luminosity – bulge mass – black hole mass relation: the average absolute R-band magnitude for the Smith et al. sample ($-23.71 \pm 0.12$, assuming V-R=0.6) is the same as that for the radio galaxies in the Dunlop et al. sample ($-23.66 \pm 0.16$), indicating that the properties of the host galaxies in the two samples are the same. Note that the differences between these methods result mainly in an uncertainty in the absolute values of $M_{bh}$, not in their relative values. All the radio galaxies are within the allowed range of radio power for their black hole masses as proposed by Dunlop et al. (2002).

### 4.4 Connecting the local populations of radio galaxies and inactive ellipticals

Since the radio galaxies are selected virtually independently of their optical properties, and the optically selected galaxies independently of their radio properties, the samples can be used to connect the two populations. Figure 8 shows that there is a clear difference between the $M_{bh}$ distribution for radio selected and optically selected AGN, with those selected in the radio, being biased towards lower black hole masses. We believe this is the natural consequence of the Faber et al. sample strongly favouring intrinsically more luminous galaxies, caused by its apparent magnitude limit. In contrast, the selection of objects on radio emission is practically volume based, with the parent population of potential radio-loud AGN containing relatively many more galaxies with lower velocity dispersions and black hole masses than the Faber et al. sample, which causes the sample of radio-selected AGNs to cover more galaxies with low $M_{bh}$.

These black hole mass distributions form the key to understand the connection between the populations of radio-loud and radio-quiet galaxies. First we determined the fraction of radio-loud AGN in the Faber et al. sample as a function of black hole mass. This is shown in figure 9, with the solid and dotted lines indicating the fraction of galaxies with $P_{1.4GHz} > 23.0$ W/Hz respectively, the former decreasing from about 1/5 at $M_{bh} = 10^2 M_\odot$ to < 1/20 at $M_{bh} = 10^5$. Note that a different subsample has been used for this than in figure 8, with such a distance limit that it can be determined from the NVSS whether the galaxy has a radio power above or below the cut-off. The dashed line shows the fraction of objects as function of $M_{bh}$ with a radio power more than 100 times that expected for the $M_{bh} - P_{radio}$ relation by Franceschini et al (1998). It shows that although the radio selected AGN do not have black holes with $M_{bh} < 3 \times 10^2 M_\odot$, black holes below this mass can still be active but only with a very low probability. Several objects with $M_{bh} \sim 10^2 M_\odot$ have been found with extended double-lobed low power radio sources in the Faber et al. sample.

With this estimate of the fraction of black holes producing powerful radio sources as a function of $M_{bh}$, the populations of radio-loud and radio-quiet galaxies can be linked. The absolute magnitude of a galaxy is connected to its central velocity dispersion by the Faber-Jackson relation (Faber & Jackson 1976), which in itself is related to the black hole mass via the $M_{bh} - \sigma$ relation. In this way, the local distribution of black hole masses can be roughly deduced from the local galaxy luminosity function. The combination of the Faber-Jackson relation, which was re-determined for $\sigma$ from the galaxies in the Faber et al. sample, and the $M_{bh} - \sigma$ relation, results in a local black hole mass distribution of

$$dN/dM_{bh} = 0.75 \phi^*(M_{bh}) \exp \left( -\frac{M_{bh}}{M_*} \right)^{0.65} \left( \frac{M_{bh}}{M_{\odot}} \right)^{0.55(1+\alpha)} dM_{bh}$$

with $\log M^* = -8.818 + 0.75 M_\odot/1.616$, where $M_\odot$, $\alpha$, and $\phi^*$ are the Schechter Function parameters of the local luminosity function in B band. Our estimate of the fraction of black holes producing powerful radio sources should now link this distribution of $M_{bh}$ to the local radio luminos-
ity function. For our calculation we assume that the fraction of radio-loud black holes with $P_{1.4\,\text{GHz}} > 23.0\,\text{W/Hz}$ is $0.25 \times (1 + (M_{bh}/1.5 \times 10^8 M_{\odot})^2)$, which is represented by the smooth curve in figure 9. Using the Schechter parameters for the local luminosity function of elliptical galaxies only, as derived from the 2dF Galaxy Redshift Survey (type 1 gals; Madgwick et al., 2002) we derive a local radio source density of $1.6 \times 10^{-5}\,\text{Mpc}^{-3}$ at $\log P_{1.4\,\text{GHz}} > 23.0\,\text{W/Hz}$. This corresponds very well to the density of radio sources above this luminosity cutoff as derived from the local radio luminosity function, which is $1.3 \times 10^{-5}\,\text{Mpc}^{-3}$ (eg. Dunlop & Peacock, 1990). In addition, the distribution of the black hole masses in the radio selected samples is shown in Figure 10. Although these samples are not complete, we believe that they are roughly selected at random from the general population of radio sources with $\log P_{1.4\,\text{GHz}} > 24.0\,\text{W/Hz}$. The smooth curve represents the expected distribution of black hole masses from the calculations above, which is strikingly similar. These results confirm that elliptical galaxies must comprise the large majority of the radio-loud population of active galaxies.

5 SUMMARY

We have determined the fundamental galaxy parameters for a sample of 7 host galaxies of young radio-loud AGN at $z<0.3$, and have shown that they follow the fundamental plane of elliptical galaxies. There is some indication that the more distant objects in the sample have higher M/L ratios, as expected from stellar evolution. As these galaxies with young radio sources are relatively easy to select, and the contributions of the AGN light to the optical spectra are minimal, they can readily be used to study the evolution of the fundamental plane out to $z=1$, independent of optical selection effects.

Black hole masses are determined for the young radio-loud AGN, and for samples of classical radio galaxies and optically selected ellipticals, using the $M_{bh} - \sigma$ relation. We confirm the relation between radio power and black hole mass as found by Franceschini et al. (1998), but only for relatively passive ellipticals. Active galaxies do not show such a correlation and can range over 7 orders of magnitude in radio power at a given $M_{bh}$.

The local galaxy luminosity function was combined with the Faber-Jackson relation and the $M_{bh} - \sigma$ relation to obtain the local distribution of black hole masses. This, combined with the fraction of black holes with powerful radio sources as function of $M_{bh}$, which was determined from the optically selected sample, results in a radio source density and radio-loud black hole mass distribution. These are found to be consistent with the local radio luminosity function and the distribution of black hole masses in the radio-selected samples, and confirms that elliptical galaxies must comprise the large majority of the radio-loud population of active galaxies.

ACKNOWLEDGEMENTS

The William Herschel Telescope, the Isaac Newton Telescope, and the Jacobus Kapteyn Telescope are operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos at the Instituto de Astrofisica de Canarias. We wish to thank the service team of the ING and Dr. Karl-Heinz Mack for taking the JKT data.

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