The Evolution of 3CR Radio Galaxies from $z=1$

R.J. McLure and J.S. Dunlop

Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh, EH9 3HJ

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**ABSTRACT**

We present the results of a comprehensive re-analysis of the images of a virtually complete sample of 28 powerful 3CR radio galaxies with redshifts $0.6 < z < 1.8$ from the HST archive. Using a two-dimensional modelling technique we have derived scalelengths and absolute magnitudes for a total of 16 3CR galaxies with a median redshift of $z=0.8$. Our results indicate that the galaxy scalelengths were systematically over-estimated in the original analysis by Best, Longair & Rottgering (1997, 1998), and we find that the scalelength distribution of 3CR galaxies at $z \simeq 1$ is indistinguishable from that derived for their low-redshift counterparts from our own recently-completed HST study of AGN hosts at $z \simeq 0.2$. This finding effectively removes an important piece of the evidence that 3CR radio galaxies at $z \simeq 1$ are dynamically different from 3CR galaxies at low redshift. Moreover, for a 10-object sub-sample we have determined the galaxy parameters with sufficient accuracy to demonstrate, for the first time, that the $z \simeq 1$ 3CR galaxies follow a Kormendy relation which is indistinguishable from that displayed by low-redshift ellipticals if one allows for purely passive evolution. The implied rather modest level of passive evolution since $z \simeq 1$ is consistent with that predicted from spectrophotometric models provided one assumes a high formation redshift ($z \geq 4$) within a low-density Universe. We conclude that there is no convincing evidence for significant dynamical evolution among 3CR galaxies in the redshift interval $0 < z < 1$, and that simple passive evolution remains an acceptable interpretation of the $K-z$ relation for powerful radio galaxies.

**Key words:** galaxies: active – galaxies: evolution – galaxies: fundamental parameters

1 INTRODUCTION

It has been known since the early 1980’s that the hosts of powerful radio galaxies display a tight relation between the $K$-band magnitude and redshift (Lilly & Longair 1984). In recent years it has been shown that, at least out to $z = 1$, essentially the same relation is followed by both the less powerful Parkes Selected Regions (PSR) and 6C radio galaxies (Dunlop et al. 1989; Eales et al. 1997) and by brightest cluster galaxies (Aragon-Salamanca et al. 1998, Collins & Mann 1997). When the $K$-band magnitudes of the 3CR galaxies are corrected for the expected effects of passive evolution of their stellar populations they appear to represent rather good standard candles from the present day out to redshift one and greater. Consequently, for many years it was widely accepted that the tightness of the $K-z$ relation for the 3CR radio galaxies could be most naturally explained by the most powerful radio galaxies having a rather well-defined mass, being formed at $z \gg 1$, and evolving basically passively thereafter.

However, this long-held view has recently been challenged in a series of papers by Best, Longair & Rottger-
ing (1997, 1998), henceforth BLR. Between 1994–1996 BLR undertook an extensive study of a virtually complete sample of 28 powerful FRII 3CR galaxies in the redshift range $0.6 < z < 1.8$ (see Fig 1). BLR obtained V and I–band HST images, J and K–band UKIRT images, and complimentary radio observations at 8.4 GHz with the VLA.

BLR made use of the four broad–band images they obtained for each of their sources to perform spectral synthesis fitting. The four broad–band fluxes where fitted by a simple two–component model consisting of an old stellar population and a power–law contribution which represented any possible aligned component. The stellar population SED’s were constructed from the models of Bruzual & Charlot (1993), and assumed a 1–Gyr burst of star formation at alignment.

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to be strengthened at redshifts of $z \sim 1$ where the angular separation between companion objects and the target can easily be of the same order as the typical seeing experienced during the BLR UKIRT observations.

Given these considerations it was felt worthwhile to re-examine the publicly available HST data to determine whether the use of the full two-dimensional analysis utilised in the $z \sim 0.2$ quasar host galaxy programme would produce significantly different scalelength figures from those published by BLR.

2 DATA REDUCTION

All the HST images taken of the 3CR galaxies in the 28-object BLR sample were obtained from the HST archive facility*. A detailed list of redshifts, filters and exposure times can be found in Table 1 of BLR (1997). An investigation of the shorter-wavelength exposures of each object (mainly F555W, F622W) confirmed that they were either of insufficient signal-to-noise to be useful, or dominated by emission aligned with the radio axis. Of the 28 objects in the sample, preliminary analysis of the $I$-band images revealed a total of 16 which could be successfully modelled with our two-dimensional technique. The observational parameters of these 16 objects are detailed in Table 1 and illustrated as part of the full sample in Fig 2.

For each object there are two CR-split $I$-band exposures of unequal length available, together giving a typical exposure time of $\sim 1800$ seconds. The initial processing of the images, flat-fielding and bias removal, was carried out by the standard HST pipeline. The two exposures were then combined using the IRAF task CRREJ, which successfully removes cosmic ray events using a sophisticated sigma-clipping algorithm. The next step in the reduction process was the fitting of a plane to the image with the 3CR galaxy masked out, to accurately determine the sky background while allowing for any residual flat-fielding gradients that may have been present. The final step was the production of a two-dimensional mask for each source which eliminated any companion objects, or aligned emission, from the model-fitting process, as well as any regions of the image that could have been biased by scattered light from nearby bright stars. The advantage of being able to mask-out substantial areas of the image while still being able to run the model fitting in two-dimensions has allowed us to make greater use of the HST data than BLR.

2.1 Empirical PSF Determination

Simple radial surface-brightness plots for the 16 objects chosen for modelling reveals that there is sufficient signal-to-noise to allow fitting to a typical radius of $\sim 4''$. It is therefore necessary to have a point spread function (PSF) to convolve our model galaxies with which has good signal-to-noise out to at least this radius. Due to the synthetic PSF's produced by the TINYTIM software package (Krist 1995) being unable to reproduce the WFPC2's scattered light halo outside a radius of $\sim 1.5''$, it is clear that an empirical PSF is required for the modelling of these data. A glance at Table 1 reveals that all of the exposures utilised here were imaged through either the F785LP or F814W filters. This required the acquisition of two relatively deep PSF's imaged with the correct filter/chip combination, which were also located close to the average chip position of the 3CR galaxies, in order to avoid the noticeable positional variation of the WFPC2 PSF. An interrogation of the HST PSF search tool† produced disappointing results, with all available PSF's either too faint or too small in angular extent.

Fortunately, two suitable stars were present on the exposures of 3C41 (F785LP) and 3C239 (F814W). Due to the need for sufficient depth in the PSF wings, both of these stars had saturated cores in even the shortest exposures. To overcome this problem a modified version of the PSF resampling technique described in McLure et al 1999b was implemented. Both PSF's were only saturated within a radius of $\leq 0.3''$ of their core, well inside the radius where TINYTIM can accurately reproduce the empirical PSF. Making use of this, the two PSF's had their core replaced with the equivalent TINYTIM model, the relative scaling being determined by matching the flux in an annulus between $0.4'' < r < 0.7''$. Another advantage of this approach is that due to TINYTIM's ability to produce model PSF's at up to 50 times oversampling, sub-pixel centring of the PSF can be matched to that of the galaxies to an accuracy of $\leq 0.005''$. Although not as crucial as with the quasar host work it is still important to overcome the severe undersampling of WFPC2, especially as several of the 3CR galaxies modelled proved to have a substantial point-source contribution.

3 MODELLING

The modelling of these objects proceeded in an identical fashion to that of the $z \sim 0.2$ AGN sample studied by McLure et al. (1999a) and Dunlop et al. (1999). Each object was modelled with both a standard Freeman disc template

\* http://archive.stsci.edu

† http://www.stsci.edu/instruments/wfpc2/
Table 1. The results of the two-dimensional modelling of the 16-objects from the Best et al. z ≃ 1 3CR sample which did not suffer from excessive aligned emission. Listed in column 5 are the fitted scalelengths in kpc, with the surface-brightness at that scalelength in Cousins I-magnitudes arcsec$^{-2}$ given in column 6. Column 7 lists the integrated apparent I-band magnitude of the best-fit host galaxy with column 8 giving the ratio of the integrated luminosity of the best-fit nuclear component and host galaxy. Objects labelled with a * are members of the 10-object sub-sample.

<table>
<thead>
<tr>
<th>Source</th>
<th>z</th>
<th>Filter</th>
<th>Exp Time/s</th>
<th>$r_{1/2}$/kpc</th>
<th>$\mu_{1/2}$</th>
<th>$I_c$</th>
<th>$L_{nuc}/L_{host}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C22</td>
<td>0.938</td>
<td>F814W</td>
<td>1400</td>
<td>5.5</td>
<td>22.3</td>
<td>19.8</td>
<td>0.306</td>
</tr>
<tr>
<td>3C34$^*$</td>
<td>0.690</td>
<td>F785LP</td>
<td>1700</td>
<td>21.9</td>
<td>24.2</td>
<td>18.6</td>
<td>0.002</td>
</tr>
<tr>
<td>3C41$^*$</td>
<td>0.795</td>
<td>F785LP</td>
<td>1700</td>
<td>6.2</td>
<td>22.2</td>
<td>19.5</td>
<td>0.170</td>
</tr>
<tr>
<td>3C49$^*$</td>
<td>0.621</td>
<td>F814W</td>
<td>1400</td>
<td>10.7</td>
<td>23.0</td>
<td>19.0</td>
<td>0.000</td>
</tr>
<tr>
<td>3C65</td>
<td>1.176</td>
<td>F814W</td>
<td>1700</td>
<td>9.3</td>
<td>22.6</td>
<td>19.3</td>
<td>0.050</td>
</tr>
<tr>
<td>3C217</td>
<td>0.897</td>
<td>F814W</td>
<td>1700</td>
<td>4.1</td>
<td>22.0</td>
<td>20.1</td>
<td>0.007</td>
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<td>1.781</td>
<td>F785LP</td>
<td>1700</td>
<td>8.1</td>
<td>22.6</td>
<td>19.3</td>
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<tr>
<td>3C239</td>
<td>1.105</td>
<td>F814W</td>
<td>1700</td>
<td>6.5</td>
<td>23.3</td>
<td>20.5</td>
<td>0.000</td>
</tr>
<tr>
<td>3C247$^*$</td>
<td>0.749</td>
<td>F814W</td>
<td>1700</td>
<td>5.8</td>
<td>22.5</td>
<td>19.7</td>
<td>0.005</td>
</tr>
<tr>
<td>3C277.2$^*$</td>
<td>0.766</td>
<td>F814W</td>
<td>1800</td>
<td>17.2</td>
<td>24.9</td>
<td>20.0</td>
<td>0.063</td>
</tr>
<tr>
<td>3C289</td>
<td>0.967</td>
<td>F814W</td>
<td>1800</td>
<td>5.8</td>
<td>22.5</td>
<td>19.8</td>
<td>0.055</td>
</tr>
<tr>
<td>3C337$^*$</td>
<td>0.775</td>
<td>F785LP</td>
<td>1700</td>
<td>3.9</td>
<td>21.3</td>
<td>19.5</td>
<td>0.000</td>
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<tr>
<td>3C352$^*$</td>
<td>0.806</td>
<td>F814W</td>
<td>1800</td>
<td>14.2</td>
<td>24.7</td>
<td>19.6</td>
<td>0.024</td>
</tr>
<tr>
<td>3C441$^*$</td>
<td>0.708</td>
<td>F785LP</td>
<td>1700</td>
<td>9.6</td>
<td>22.7</td>
<td>18.9</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Table 2. The apparent characteristic surface-brightness and absolute magnitudes of the 10-object sub-sample.

<table>
<thead>
<tr>
<th>Source</th>
<th>$z$</th>
<th>$\mu_{1/2}$</th>
<th>$M_{Ic}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C34</td>
<td>0.690</td>
<td>21.0</td>
<td>−25.6</td>
</tr>
<tr>
<td>3C41</td>
<td>0.795</td>
<td>18.7</td>
<td>−25.2</td>
</tr>
<tr>
<td>3C49</td>
<td>0.621</td>
<td>20.1</td>
<td>−25.0</td>
</tr>
<tr>
<td>3C226</td>
<td>0.820</td>
<td>19.0</td>
<td>−25.5</td>
</tr>
<tr>
<td>3C247</td>
<td>0.749</td>
<td>20.7</td>
<td>−25.9</td>
</tr>
<tr>
<td>3C277.2</td>
<td>0.766</td>
<td>19.1</td>
<td>−24.9</td>
</tr>
<tr>
<td>3C337$^*$</td>
<td>0.635</td>
<td>19.5</td>
<td>−24.2</td>
</tr>
<tr>
<td>3C340</td>
<td>0.775</td>
<td>17.8</td>
<td>−25.1</td>
</tr>
<tr>
<td>3C352</td>
<td>0.806</td>
<td>21.1</td>
<td>−25.2</td>
</tr>
<tr>
<td>3C441</td>
<td>0.708</td>
<td>19.5</td>
<td>−25.4</td>
</tr>
</tbody>
</table>

Figure 3. The F814W filter profile including the system response and quantum efficiency of WFPC2. Also shown is the location of the 4000Å break of an elliptical galaxy spectrum observed at a redshift of $z = 0.9$. 

4 RESULTS

In this section the scalelength, absolute luminosity and Kormendy relation results from our two-dimensional modelling of the $z \simeq 0.8$ objects are presented. Due to the significant effect that choice of cosmology can have on angular diameter, cosmological dimming and look-back time over this redshift range, we give these results for a range of possible cosmologies. Four different representative scenarios are considered featuring two values of $H_0 (50, 70)$, together with both open ($\Omega_0 = 0.1$) and flat ($\Omega_0 = 1$) geometry.

The results from the modelling of all 16 HST objects are presented in Table 1. The main conclusions reached from this modelling work are based largely on the results for a 10-object sub-sample. The sub-sample consists of the low-redshift end of the BLR sample and is illustrated in Fig 2.
The results of our determination of galaxy half-light radius \( r_e \) for the 10-objects in the \( z \approx 0.8 \) sub-sample are presented in Table 3. Two features of this table are immediately obvious. \( \Omega_0 \) and \( H_0 \) have been kept constant in all four cosmologies, consistent with the suggestion from Fig 4 that the distribution of scalelengths from the full 16-object sample, and indeed our 20 radio-loud AGN at \( z \approx 0.2 \), has a substantial tail toward high values.

Given that the scalelength results obtained by BLR are quoted assuming \( H_0 = 50, \Omega_0 = 1 \) it is straightforward to investigate what differences exist between their scalelength determinations and those presented here. Due to the fact that most of the BLR scalelength information is derived from their \( K \)-band observations rather than the HST images, it is not the case that they have published a scalelength value for each of the objects re-modelled in this paper. In order to perform a comparison between the two sets of results it has been necessary to simply base the BLR figures on the 8-objects from our 10-object sub-sample for which they have derived a scalelength value.

Assuming \( H_0 = 50, \Omega_0 = 1 \) the mean scalelength of the 10-object sample is \( r_e = 12.61 \pm 2.26 \) kpc with a median of 9.70 kpc. The corresponding BLR-derived values for 8 of these 10 objects are \( r_e = 15.15 \pm 2.17 \) kpc with a median of 14.95 kpc. Given the small number statistics that are available, and the inherent difficulty in constraining galaxy scalelengths, the median is the more robust measure of the typical scalelength. Using the median it can be seen from these figures that the one-dimensional analysis technique employed by BLR has systematically overestimated the characteristic size of the 3CR galaxies by \( \approx 50\% \).

\[
\begin{array}{|c|c|c|c|}
\hline
\Omega_0 & H_0 & \text{median } r_e / \text{kpc} & \left< r_e \right> / \text{kpc} \\
\hline
1 & 50 & 9.7 & 12.6 \pm 2.3 \\
1 & 70 & 8.2 & 9.3 \pm 1.6 \\
0.1 & 50 & 11.5 & 14.8 \pm 2.7 \\
0.1 & 70 & 8.2 & 10.6 \pm 1.9 \\
\hline
\end{array}
\]

Table 3. The scalelength results from the two-dimensional modelling of the \( z \approx 0.8 \) sub-sample. Columns one and two detail the choice of cosmology. Column three gives the median scalelength values for the 10-objects in the sample. Column four gives the corresponding mean values together with the standard error.

The remaining 6 objects \( (z \geq 0.9) \) have been excluded from the following analysis due to the incursion of the 4000\AA{} break into the HST F814W filter. The throughput of the F814W filter is shown in Fig 3 complete with the system response and CCD quantum efficiency. As can be seen from this figure, for objects with redshifts \( z \geq 0.9 \) this filter will bridge the 4000\AA{} break, meaning that it can no longer be assumed that the detected flux has originated from the dominant old stellar population. Given that the alignment effect in radio galaxies is stronger in the rest-frame UV than at longer wavelengths it is to be expected that these objects are contaminated by a significant aligned component. The 10-object sub-sample has the advantage of having a tight \( r_1/2 \) distribution with a mean of 0.74 \( \pm \) 0.07 and a median of 0.76, which is well matched by the distribution of the 10 radio galaxies studied at low-\( z \), with its mean redshift of 0.20 \( \pm \) 0.04 and median of 0.20. This allows a direct comparison between the two samples without the added complication of allowing for significant evolutionary effects within the samples themselves.

### 4.1 Scalelengths

The results of our determination of galaxy half-light radius \( r_e \) for the 10-objects in the \( z \approx 0.8 \) sub-sample are presented in Table 3. Two features of this table are immediately obvious. The corresponding mean values together with the standard error.
Table 4. The absolute $I$-band magnitudes of the two 10-object radio galaxy sub-samples. Column four gives the median figures with column five listing the corresponding mean figures complete with standard error.

<table>
<thead>
<tr>
<th>$\Omega_0$</th>
<th>$H_0$</th>
<th>$z$</th>
<th>Median $M_I$</th>
<th>$&lt; M_I&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>50</td>
<td>0.2</td>
<td>$-24.52$</td>
<td>$-23.45\pm0.16$</td>
</tr>
<tr>
<td>1.0</td>
<td>50</td>
<td>0.8</td>
<td>$-24.60$</td>
<td>$-24.62\pm0.13$</td>
</tr>
<tr>
<td>1.0</td>
<td>70</td>
<td>0.2</td>
<td>$-23.69$</td>
<td>$-23.72\pm0.16$</td>
</tr>
<tr>
<td>1.0</td>
<td>70</td>
<td>0.8</td>
<td>$-23.87$</td>
<td>$-23.89\pm0.13$</td>
</tr>
<tr>
<td>0.1</td>
<td>50</td>
<td>0.2</td>
<td>$-24.54$</td>
<td>$-24.55\pm0.16$</td>
</tr>
<tr>
<td>0.1</td>
<td>50</td>
<td>0.8</td>
<td>$-24.98$</td>
<td>$-25.07\pm0.18$</td>
</tr>
<tr>
<td>0.1</td>
<td>70</td>
<td>0.2</td>
<td>$-23.80$</td>
<td>$-23.81\pm0.16$</td>
</tr>
<tr>
<td>0.1</td>
<td>70</td>
<td>0.8</td>
<td>$-24.25$</td>
<td>$-24.24\pm0.13$</td>
</tr>
</tbody>
</table>

Table 5. The best-fitting Kormendy relations for the 10 $z\sim0.8$ 3CR galaxies under four different choices of cosmology.

\[
\begin{align*}
\mu_{1/2} &= 3.51\pm0.36 \log r_{1/2} + 16.53\pm0.38 & \Omega_0 &= 1.0 & H_0 &= 50 \\
\mu_{1/2} &= 3.51\pm0.36 \log r_{1/2} + 17.05\pm0.33 & \Omega_0 &= 1.0 & H_0 &= 70 \\
\mu_{1/2} &= 3.51\pm0.38 \log r_{1/2} + 16.28\pm0.42 & \Omega_0 &= 0.1 & H_0 &= 50 \\
\mu_{1/2} &= 3.51\pm0.38 \log r_{1/2} + 16.80\pm0.37 & \Omega_0 &= 0.1 & H_0 &= 70
\end{align*}
\]

4.2 Absolute Magnitudes

The absolute Cousins $I$-band magnitudes for the $z \sim 0.8$ and $z \sim 0.2$ sub-samples are listed in Table 4 for the four different cosmologies. The values shown are calculated from integrating the best-fit de Vaucouleurs profile to infinite radius in order to be consistent with the published results for integrating the best-fit de Vaucouleurs profile to infinite radius in different cosmologies. The values shown are calculated from the use of the expanded samples strengthens the conclusion that the BLR scalelengths are overestimated, with the median BLR scalelength being $\approx 70\%$ greater than the two-dimensional modelling results presented here.

In light of this, the method used to convert the F785LP fluxes for each host to the equivalent F814W figure, and hence Cousins $I$-band magnitude, was to predict the count rates $R_{\text{object}}$ (erg$^{-1}$s$^{-1}$pixel$^{-1}$) of a source of apparent visual magnitude $V$ in the two filters using the filter ratios of Holtzman et al. 1995.

The cosmology-independent k-corrections for each object, produced by the blueward shifting of the $I$-band filter along the galaxy spectrum with increasing redshift, were calculated from the figures presented for a burst-elliptical galaxy by Rocca-Volmerange & Guiderdoni (1988). Given that the predictions produced by different spectral synthesis codes can differ significantly (Charlot et al. 1996) it was considered worthwhile to make an independent check of the validity of these k-corrections. Due to the restriction of this analysis to the 10-object sub-sample, for which the images sample galaxy light longward of the 4000Å break, it is possible to estimate the necessary cosmological k-corrections by modelling the galaxy spectrum as a power-law of the form $f_\nu \propto \nu^{-\alpha}$, where $\alpha$ is the spectral index. The value of $\alpha$ appropriate for radio galaxies imaged in the $I$-band was estimated to be $\alpha \approx 2$ from a typical old ($\geq 12$Gyr) elliptical galaxy spectrum. This is in good agreement with the value of $\alpha = 1.82$ needed to reproduce the k-corrections of Rocca-Volmerange and Guiderdoni (1988). The question of whether the absolute magnitudes presented in Table 4 are substantially different from the results previously obtained for the $z = 0.2$ radio galaxies is addressed within Section 5.

4.3 The Kormendy Relation

Given that the hosts of the 10 radio galaxies within the sub-sample are well fitted by a standard de Vaucouleurs galaxy template, it is interesting to see whether the parameters obtained from these fits produce a Kormendy relation comparable to that followed by both low-$z$ inactive ellipticals (and the hosts of the $z = 0.2$ AGN, see Section 5). The $\mu_{1/2}$ values required to construct the Kormendy relation have been corrected for the cosmological dimming of surface-brightness according to:

\[
I_1 = \frac{(1+z_2)^{3\alpha}}{(1+z_1)^{3\alpha}}
\]

where a value of $\alpha = 1.8$ has been assumed. The resulting $\mu_{1/2} - r_{1/2}$ relation for the four cosmologies are shown in Table 5. It is clear from this that the choice of cosmology makes no significant difference to the slope of the Kormendy relation (as expected given the small redshift range of the objects), and that in all cases this slope is consistent with...
that of $\simeq 3$ displayed by inactive low-\(z\) ellipticals (Kormendy 1977).

It is worth noting that the $r_{1/2}$ and $\mu_{1/2}$ parameters from the one-dimensional modelling of BLR failed to produce a $\mu_{1/2} - r_{1/2}$ relation which was consistent with the expected slope of $\simeq 3$. The modelling results of BLR had the $z \simeq 1$ 3CR galaxies lying along a constant luminosity slope of 5, exactly as is expected when the galaxy luminosities have been well determined but the scalelengths have not been constrained (Abraham et al. 1992). The fact that the relation presented above is consistent with the Kormendy relation, within the errors, can therefore be taken as further evidence that our two-dimensional modelling has been much more successful in constraining the scalelengths of the sub-sample objects. The possibility of using the Kormendy relations derived above to test for the effects of passive or dynamical evolution is explored in section 5.3.

### 5 COMPARISON WITH LOW-REDSHIFT RADIO GALAXIES

#### 5.1 Scalelengths

The derived median and mean scalelengths for the 10-source $z \simeq 0.2$ radio galaxy sample from our low-\(z\) AGN host galaxy study (McLure et al. 1999a, Dunlop et al. 1999) are presented in Table 6. A comparison of these results with those presented for the $z \simeq 0.8$ sub-sample in Table 3 shows the two groups of galaxies to have very similar characteristic scalelengths. The poorest agreement between the two sets of results is for the $\Omega_0 = 1.0$, $H_0 = 50$ cosmology. However, even in this case the figures are consistent to within the errors. In the other three cosmologies the median and mean scalelengths for the two samples are virtually identical, differing by $\leq 0.5$ kpc in all cases. The similarity between the scalelength distributions of the two sub-samples is confirmed by an application of the Kolmogorov–Smirnov (KS) test. For the two $\Omega_0 = 1.0$ cosmologies the KS test returns a probability of 0.68 that the two samples are drawn from the same underlying distribution. This conclusion is even stronger in the $\Omega_0 = 0.1$ cosmologies where the KS test returns a probability of 0.97 that the two distributions are the same. Therefore, contrary to the results of BLR, we find no evidence that the galaxies comprising the $z \simeq 0.8$ sub-sample are systematically larger than their $z \simeq 0.2$ counterparts.

### 5.2 Absolute Luminosity

In order to allow a direct comparison of the characteristic luminosities of the low- and high-redshift radio galaxy sub-samples, and thereby look for any evidence of significant merger activity, it is first necessary to correct for the different filters and the expected passive evolution of the stellar populations. To achieve this it was decided to convert the $z \simeq 0.2$ $R$-band magnitudes to their $I$-band equivalents, and then to predict the brightening of the stellar population between $z = 0.2$ and $z = 0.8$ due to passive evolution alone. The present-day colour of an elliptical galaxy formed at high redshift ($z \geq 3$) has been taken as $R - I = 0.7$ (Fukugita et al. 1995). The corrections to be made for the effects of passive evolution have been calculated using the synthetic galaxy spectral models of Jimenez et al. (1996) using our chosen set of four possible cosmologies. Several different galaxy formation redshifts were considered to investigate their effects on the resulting correction. A comparison between the predicted amount of $I$-band passive evolution between $z = 0.2$ and $z = 0.8$ and the difference in median absolute luminosity of the two samples is presented in Table 7.

It is immediately clear from these results that the difference in absolute $I$-band luminosity between the $z \simeq 0.2$ and $z \simeq 0.8$ samples is inconsistent with the amount of passive evolution predicted by the stellar synthesis models within the two Einstein-de Sitter cosmologies. This is still true even in the $\Omega_0 = 1.0$ model which allows present-day ellipticals to be as old as possible ($z_{for} = 10$, $H_0 = 50$); this model still requires 2.5 times more magnitudes of passive evolution than is seen in the data.

Adoption of either of the open cosmologies results in a measured difference in absolute luminosity of $\simeq 0.5$ mags between the two galaxy samples (columns 3 & 4). As can be seen from Table 7, this luminosity difference is formally consistent with the expected passive evolution in both open cosmologies, for all alternative formation redshifts. However, it is interesting to note from Table 7 that the $H_0 = 70$, $\Omega_0 = 0.1$ cosmology clearly provides the best match between the data and the spectrophotometric model predictions. In this cosmological picture the model predictions are perfectly consistent with the data for all star formation redshifts of $z \geq 4$, in good agreement with recent discoveries of old stellar population ellipticals at redshifts of $z = 1.5 \rightarrow 2$ (Dunlop et al. 1996, Spinrad et al. 1997, Stiavelli et al. 1999).

<table>
<thead>
<tr>
<th>$\Omega_0$</th>
<th>$H_0$</th>
<th>median $r_{1/2}$ / kpc</th>
<th>$&lt; r_{1/2} &gt;$ / kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>11.3</td>
<td>13.8 ± 2.2</td>
</tr>
<tr>
<td>1</td>
<td>70</td>
<td>8.1</td>
<td>9.8 ± 1.6</td>
</tr>
<tr>
<td>0.1</td>
<td>50</td>
<td>11.9</td>
<td>14.4 ± 2.3</td>
</tr>
<tr>
<td>0.1</td>
<td>70</td>
<td>8.5</td>
<td>10.3 ± 1.6</td>
</tr>
</tbody>
</table>

Table 6. The scalelength results from the two-dimensional modelling of the $z \simeq 0.2$ sub-sample. Columns one and two detail the choice of cosmology. Column three gives the median scalelength values for the 10-objects in the sample. Column four gives the corresponding mean values together with the standard error.

<table>
<thead>
<tr>
<th>$\mu_{1/2}$</th>
<th>$r_{1/2}$</th>
<th>$I$-band passive evolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{1/2} = 2.86 \pm 0.34 \log r_{1/2} + 17.66 \pm 0.38$</td>
<td>$\Omega_0 = 1.0$, $H_0 = 50$</td>
<td></td>
</tr>
<tr>
<td>$\mu_{1/2} = 2.86 \pm 0.34 \log r_{1/2} + 18.08 \pm 0.33$</td>
<td>$\Omega_0 = 1.0$, $H_0 = 70$</td>
<td></td>
</tr>
<tr>
<td>$\mu_{1/2} = 2.85 \pm 0.34 \log r_{1/2} + 17.61 \pm 0.42$</td>
<td>$\Omega_0 = 0.1$, $H_0 = 50$</td>
<td></td>
</tr>
<tr>
<td>$\mu_{1/2} = 2.85 \pm 0.34 \log r_{1/2} + 18.03 \pm 0.37$</td>
<td>$\Omega_0 = 0.1$, $H_0 = 70$</td>
<td></td>
</tr>
</tbody>
</table>

Table 8. The best-fitting Kormendy relations for the 10 $z \simeq 0.2$ radio galaxies under four different choices of cosmology.
Table 7. The results of the tests to determine the influence of different cosmology and formation redshift upon the amount of passive evolution expected between $z=0$ and $z=0.2$. Columns one and two list the cosmological parameters for each test. Column three lists the amount of evolution required to reconcile the median of the two absolute magnitude distributions. Column four gives the corresponding mean figures complete with standard errors. Columns 5-7 list the amount of passive evolution between $z=0.2$ and $z=0.8$ predicted by our spectrophotometric modelling for three galaxy formation redshifts. (The apparently anomalous trend displayed by the $\Omega_0 = 1, H_0 = 70, z_{for} = 3$ model is due to the fact that even at $z=0.2$ a galaxy is only 6 Gyr old, and remains relatively bright at 1.)

<table>
<thead>
<tr>
<th>$\Omega_0$</th>
<th>$H_0$</th>
<th>$\Delta M_{med}$</th>
<th>$\Delta M_{mean}$</th>
<th>$\Delta M_{model}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>0.17</td>
<td>0.18±0.16</td>
<td>0.52</td>
</tr>
<tr>
<td>1</td>
<td>70</td>
<td>0.17</td>
<td>0.18±0.16</td>
<td>0.63</td>
</tr>
<tr>
<td>0.1</td>
<td>50</td>
<td>0.52</td>
<td>0.44±0.16</td>
<td>0.26</td>
</tr>
<tr>
<td>0.1</td>
<td>70</td>
<td>0.43</td>
<td>0.45±0.16</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Figure 5. Shown in the top-left panel is the Kormendy relation followed by the $z\simeq 0.8$ sub-sample which has a best-fit slope of 3.5. In the top-right panel the $z\simeq 0.2$ radio galaxies (crosses) have been added along with their best-fit relation of slope 2.9 (dashed line). In the bottom-left panel both galaxy sub-samples are shown with the best-fit relation forced to have a intermediate slope of 3.20. The bottom right figure shows the best-fit Kormendy relation (slope=3.21) produced by brightening the surface-brightness of the $z\simeq 0.2$ galaxies by 0.6 magnitudes.
force both alternative measures of the amount of luminosity evolution, and the predictions of the spectral modelling, into agreement. In contrast, the $\pm 1\sigma$ predictions from the Kormendy relations in the $\Omega_0 = 0.1$ cosmologies comfortably bracket the offsets given in Table 7, thus leaving both alternative measures of the luminosity evolution in excellent agreement.

In theory, the Kormendy relations for the low and high-$z$ sub-samples presented here offer an opportunity to constrain both cosmology and the prevalence of merger activity. However, in practice the effects of these are very closely coupled. For example, our results can be reproduced either by pure passive evolution since $z \approx 0.8$ in an open Universe, or by modest growth ($\approx 20\%$ growth in scalelength & luminosity) since $z \approx 0.8$ in an Einstein-de Sitter Universe. Despite this inherent degeneracy we can exclude either very strong growth ($\geq 50\%$) from mergers, as well as the apparent negative growth claimed by Best et al.

### 5.3 Kormendy Relation

If the two samples of radio galaxies can truly be linked by a single population of passively evolving ellipticals it is to be expected that they should follow Kormendy relations which are identical except for a simple vertical shift in surface-brightness. After making the appropriate surface-brightness corrections (Section 4.3) and $R - I$-band filter transformation (Section 5.2) the least-squares fit to the Kormendy relations formed by the $z \approx 0.2$ radio galaxies are shown in Table 8.

It can be seen from this that, as for the $z \approx 0.8$ galaxies, the choice of cosmology makes little difference to the slope of the Kormendy relation, although the normalization does change significantly. It is also apparent that the low-$z$ objects appear to follow a substantially flatter relation, with a slope of 2.9 instead of 3.5, although clearly both values are consistent with the expected slope $\approx 3$ (due to the fairly substantial formal error in the fitted slope, which is predominantly a result of the small sample size and lack of dynamic range). To facilitate a fair comparison of the high- and low-$z$ radio galaxy Kormendy relations, the least-squares fitting was repeated with an enforced intermediate slope of 3.20. If it is indeed the case that these two galaxy populations can be linked by passive evolution alone then the vertical shift required to reconcile the Kormendy relations should be in good agreement with both that required to match the Kormendy relations of the two samples using the best-fit scalelengths of Table 1 converted to the appropriate cosmology. Columns 3 and 5 list the vertical shift implied by shifting the best-fit scalelengths left ($-1\sigma$) and right ($+1\sigma$) until the scalelength distributions of the two sub-samples differ at the $1\sigma$ level.

<table>
<thead>
<tr>
<th>$\Omega_0$</th>
<th>$H_0$</th>
<th>$\Delta M(-1\sigma)$</th>
<th>$\Delta M$</th>
<th>$\Delta M(+1\sigma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>50</td>
<td>-0.24</td>
<td>0.43</td>
<td>0.56</td>
</tr>
<tr>
<td>1.0</td>
<td>70</td>
<td>-0.24</td>
<td>0.44</td>
<td>0.58</td>
</tr>
<tr>
<td>0.1</td>
<td>50</td>
<td>0.18</td>
<td>0.60</td>
<td>0.84</td>
</tr>
<tr>
<td>0.1</td>
<td>70</td>
<td>0.19</td>
<td>0.60</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Table 9. The amount of luminosity evolution predicted by forcing both galaxy sub-samples to lie on a Kormendy relation with slope 3.2. Column four lists the implied vertical shift required to overlay the Kormendy relations of the two samples using the best-fit scalelengths of Table 1 converted to the appropriate cosmology. Columns 3 and 5 list the vertical shift implied by shifting the best-fit scalelengths left ($-1\sigma$) and right ($+1\sigma$) until the scalelength distributions of the two sub-samples differ at the $1\sigma$ level.

### 6 CONCLUSION

The results from a thorough re-examination of the BLR HST images of a sample of $z = 1$ 3CR radio galaxies has been presented. It has been shown that, contrary to the published results of BLR, in terms of scalelength, absolute magnitudes and Kormendy relation there are no significant differences between $z \sim 0.8$ and $z \sim 0.2$ 3CR radio galaxies. The two populations appear to be fully consistent with being comprised of old stellar populations formed at high redshift and evolving passively thereafter.

It is obviously true that the fact that both the high and low-redshift radio galaxies have absolute luminosities consistent with pure passive evolution can easily be reconciled with the involvement of some dynamic evolution. In the dynamical model this simply requires that the proto-galactic clumps which merge to produce the final galaxies where formed reasonably coevally. The results presented here do not then require that these radio galaxies must have formed in a monolithic collapse at a single redshift. However, they do suggest strongly that the vast majority of merger activity within this population of massive ellipticals must have been completed before $z \approx 1$. Although this is difficult to achieve with standard $\Omega_0 = 1$ hierarchical clustering models it is not necessarily inconsistent with semi-analytical galaxy formation models in a $\Omega_0 = 0.3, \Lambda = 0.7$ cosmology, where as much as 70% of present day ellipticals can already be in place by $z \approx 1$ (Kauffmann & Charlot 1999).

The crucial question still to be answered is whether or not it can be proven that a significant difference in cluster environment does exist between the two populations. If it can be shown that this is definitely the case then the argument forwarded by BLR that we are observing the effects of dynamical evolution producing the characteristic mass required for powerful radio emission at the two different epochs remains tenable, despite the fact it cannot be detected via a significant difference in scalelengths. However, as was discussed in Section 1, while there have been numerous surveys carried out recently tackling the environments of high-$z$ radio sources, the work on the low-$z$ environments looks to be subject to possible systematic error. This suspicion is further strengthened by our new deep R-band HST
images of the 10 $z \approx 0.2$ radio galaxy sub-sample (McLure et al. 1999a, Dunlop et al. 1999). These images show numbers of apparent companion objects which appear consistent with Abell classes 0 → 2. This is in good agreement with our recent work to model the first to fourth-ranked brightest cluster galaxies (BCG) in clusters spanning Abell classes 1 → 4, imaged with HST (Dunlop et al. 1999). This work has shown that the scalelengths of these objects are not significantly different from the radio galaxy scalelength results presented here.

In an attempt to disentangle the radio galaxy environment problem, more near-infrared observations of the low-$z$ radio galaxies and quasars from our HST programme are planned, to compliment our existing R and B-band images of this sample. This combined dataset will allow a fully qualitative investigation of the cluster environments of the low-$z$ radio galaxies with which to compare with the existing high-$z$ environmental data.

If it transpires that there is no significant difference in 3CR environments at high and low-$z$, the name implies the picture of powerful radio galaxy evolution emerges. Combined with the scalelength evidence presented here, this would suggest that the host galaxies of powerful radio sources are basically the same sort of objects at all redshifts from $z = 0 \rightarrow 1$. In this picture the fall-off in 3CR radio power over this redshift range would simply be due to the progressively smaller amount of gas available to feed the central engine. Present day BCGs in this scenario have the potential to be powerful radio sources but are dormant due to not having been involved in a recent gravitational interaction with which to trigger gas in-fall, or simply to having exhausted all their available gas.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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