Morphology and surface brightness evolution of $z \sim 1.1$ radio galaxies

Nathan Roche,¹ Stephen Eales¹ and Steve Rawlings²

¹Department of Physics and Astronomy, University of Cardiff, PO Box 913, Cardiff CF2 3YB
²Department of Astrophysics, University of Oxford, Nuclear and Astrophysics Laboratory, Keble Road, Oxford OX1 3RH

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ABSTRACT

We use $K$-band (2.1-$\mu$m) imaging to investigate the angular size and morphology of 10 6C radio galaxies, at redshifts $1 \leq z \leq 1.4$. Two radio galaxies appear to be undergoing mergers, another contains, within a single envelope, two intensity peaks aligned with the radio jets, while the other seven appear consistent with being normal ellipticals in the $K$ band.

Intrinsic half-light radii are estimated from the areas of each radio galaxy image above a series of thresholds. The 6C galaxy radii are found to be significantly smaller than those of the more radio-luminous 3CR galaxies at similar redshifts. This would indicate that the higher mean $K$-band luminosity of the 3CR galaxies reflects a difference in the size of the host galaxies, and not solely a difference in the power of the active nuclei.

The size–luminosity relation of the $z \sim 1.1$ 6C galaxies indicates a 1.0–1.6 mag enhancement of their rest frame $R$-band surface brightness relative to either local ellipticals of the same size or FRII radio galaxies at $z < 0.2$. The 3CR galaxies at $z \sim 1.1$ show a comparable enhancement in surface brightness. The mean radius of the 6C galaxies suggests that they evolve into ellipticals of $L_{\star}$ luminosity, and is consistent with their low-redshift counterparts being relatively small FRII galaxies ~25 times lower in radio luminosity, or small FRI galaxies ~1000 times lower in radio luminosity. Hence the 6C radio galaxies appear to undergo as much optical and radio evolution as the 3CR galaxies.

Key words: galaxies: active – galaxies: evolution – galaxies: photometry – radio continuum: galaxies.

1 INTRODUCTION

Powerful radio galaxies at $z < 0.5$ appear similar in morphology and profile to normal giant ellipticals (Lilly, MacLean & Longair 1984), with luminosities in the range from $L_{\star}$ to ~2 mag above $L_{\star}$ and no obvious correlation between radio and optical luminosity (Laing, Riley & Longair 1983; Owen & Laing 1989; Owen & White 1991). The relative uniformity of the optical properties of radio galaxies, combined with the ease of detection at higher redshifts, means that they provide a useful probe of galaxy evolution. Lilly & Longair (1984) measured K-band (2.2-$\mu$m) magnitudes for 3CR radio galaxies over a very wide range of redshifts (the 3CR catalogue is a flux-limited sample containing the radio galaxies with 178 MHz flux exceeding 10 Jy). The K–$z$ relation of these galaxies indicated an evolutionary brightening with redshift, consistent with a high formation redshift ($z \sim 5$) followed by passive stellar evolution.

The radio luminosities ($L_{\text{rad}}$) of the most powerful radio galaxies also decrease with time. Laing et al. (1983), using a $V/V_{\text{max}}$ test, showed that the $L_{\text{rad}}$ evolution was comparable to the evolution of quasars. Padovani & Urry (1992) studied the radio evolution of the 3CR catalogue in more detail, deriving a radio luminosity function and obtaining a best fit for an exponential $L_{\text{rad}}$ evolution with time-scale $\tau = 0.17 \pm 0.02$ Gyr, i.e., $\tau = 3.3 \pm 0.4$ Gyr. It must be noted that this exponential decrease describes the evolution of the radio luminosity function, rather than that of individual radio galaxies. The galaxies might, for example, undergo short bursts of radio emission, separated by much longer periods of radio quiescence, with subsequent bursts decreasing with time in their peak radio intensity.

Higher redshift radio galaxies differ in appearance from...
normal ellipticals, especially at shorter wavelengths. Rigler et al. (1992) studied 13 3CR galaxies at $0.8 < z < 1.3$ and found that they could be decomposed into ‘active’ and ‘passive’ components. The ‘active’ components are elongated, blue (approximately $f_\text{blue}$), and aligned with the radio axis. Best, Longair & Röttgering (1996), using WFPC2 imaging, found that in radio galaxies with a relatively small separation between the radio lobes, the blue components consisted of strings of several bright knots, whereas in radio galaxies with radio lobes separated by more than $\sim 200$ kpc, the blue components were much more compact. This suggested that the elongated optical components were formed as the outward passage of the radio jets triggers large-scale star formation, and later fall back towards the galaxy centres. However, the aligned components of at least some $z \sim 1$ radio galaxies show some polarization (Tadhunter et al. 1992; Leyshon & Eales 1998), suggesting that dust-reflected light from the active nucleus is also important.

The aligned components are less prominent at longer wavelengths, typically contributing only $\sim 10$ per cent of the total flux at $\lambda_{\text{rest}} \approx 1 \mu$m (i.e., the observed K band), but many $z \sim 1$ 3CR galaxies still show some alignment between their radio axes and K-band isophotes (Dunlop & Peacock 1993; Ridgway & Stockton 1997). Most of the red light is produced by the ‘passive’ components, which are redder, diffuse and symmetric, apparently unaligned with the radio axis, and appear to be underlying giant ellipticals.

In the infrared H band (1.65 µm), Rigler & Lilly (1994) found the profile of the $z = 1.18$ radio galaxy 3C 65 to be well fitted by a bulge model with $r_e = 1.77 \pm 0.18$ arcsec. Best, Longair & Röttgering (1997), observing in the K band and with the HST WFPC2, confirmed $r_e = 1.7$ arcsec for 3C 65, and found all 21 of a sample of $z \sim 1$ 3CR galaxies to be well fitted by bulge models with $0.7 < r_e < 3.9$ arcsec. The size–luminosity relation of these galaxies was consistent with that of local ellipticals with the $\sim 1$ mag of brightening expected from passive evolution. Only two of the 21 galaxies contained substantial (> 10 per cent of total flux) nuclear point-source components, although several showed some excess of surface brightness above a bulge-model profile at large radii ($r > 35$ kpc), like that in CD galaxies, which might be evidence for a rich cluster environment.

In this paper we investigate the K-band morphology and radii of 10 galaxies at similar redshifts but with more moderate radio luminosities, selected from the 6C survey which has a flux limit about 6 times fainter than 3CR. There are some unsolved problems concerning the differences between the 3CR and 6C galaxies. First, 6C radio galaxies at $0.6 < z < 1.8$ were found to be on average 0.7 mag less luminous in the observed K band than 3CR galaxies at the same redshifts (Eales & Rawlings 1996; Eales et al. 1997), but it was unclear whether this was due solely to a greater near-infrared flux from the 3CR nuclei, or to a greater mass of stars in the 3CR galaxies. We shall investigate whether the differences in the radio and optical luminosities are related to any differences in the old stellar component visible in the K band. Secondly, as he 3CR and 6C galaxies at lower redshifts are similar in mean K-band luminosity, the $K_z$ relations of the 3CR and 6C catalogues are different in slope, the latter being consistent with no evolution. Hence, if high-redshift 6C galaxies evolve into the low-redshift 6C galaxies, they must undergo surprisingly little change in K-band luminosity - but it is also possible that their low-redshift counterparts are galaxies of lower K and radio luminosity. By determining a size–luminosity relation for the 6C galaxies and comparing with both $z \sim 1$ 3CR galaxies and low-redshift radio galaxies, we may compare the surface brightness evolution of the two catalogues and determine whether the 6C galaxies are truly non-evolving.

We assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.05$ throughout. Section 2 describes the observational data, and Section 3 the analysis and photometry. In Section 4 we describe the estimation of the sizes and morphological types of the galaxies, and in Section 5 we discuss the appearance of each individual 6C galaxy. In Section 6 we present the size–luminosity relation and compare with 3CR galaxies at similar redshifts and local radio galaxies, and in Section 7 we discuss the implications for radio galaxy evolution. Section 8 summarizes the main conclusions.

### 2 OBSERVATIONAL DATA

The observational data set of this paper consists of images centred on the 10 radio galaxies from the 6C catalogue which have known spectroscopic redshifts in the $1.0 < z < 1.4$ range ($z_{\text{mean}} = 1.11$). These data were previously used by Eales et al. (1997) in a study of the K-band luminosity evolution of radio galaxies. The 6C galaxies considered here have 151-MHz fluxes of $2.2-4.4$ Jy, corresponding at these redshifts to $L_{151 \text{MHz}} \sim 10^{26.6}$ W Hz$^{-1}$. Allington-Smith (1982) and Eales (1985) give more information on the radio source properties; Eales et al. (1997, and references therein) detail the identification of the optical counterparts, and Rawlings et al. (in preparation) describe the spectroscopic observations. For comparison we include in our data set an image of a radio-loud QSO, 5C 6.8, which lies in the same redshift range as the other objects. Table 1 lists the radio galaxy coordinates and redshifts for all 11 images.

These fields were observed over the period 1995 January 18–20 using the Redeye camera on the Canada–France Hawaii Telescope (CFHT). Redeye is a 256 × 256 H GCaTe mosaic with a pixelsize of 0.50 arcsec, covering approximately $2 \times 2$ arcmin$^2$. Each field was imaged nine times, with the camera being offset by 8 arcsec between exposures in a $3 \times 3$ grid. The observations were made in the K band, centred on a wavelength of 2.1 µm (Wainscoat & Cowie 1992) where the sky background is lower than that in the standard 2.2-µm K band. Table 2 gives the total exposure times.

### Table 1

| Radio galaxy | R.A. (equinox 2000.0) | Dec. | Radio galaxy $K$ mag | Radio galaxy Redshift |
|--------------|------------------------|------|----------------------|-----------------------|
| 6C0982+39    | 08 25 23.70 +39 19 45.55 | 17.08 ± 0.06 | 1.12 |
| 6C0943+39    | 09 46 18.70 +39 44 18.33 | 18.04 ± 0.06 | 1.04 |
| 6C1011+38    | 10 14 12.86 +36 17 17.98 | 17.80 ± 0.06 | 1.04 |
| 6C1017+37    | 10 20 39.94 +36 57 07.13 | 16.84 ± 0.07 | 1.05 |
| 6C1123+54    | 11 26 23.73 +33 45 26.14 | 17.70 ± 0.03 | 1.23 |
| 6C1129+37    | 11 32 35.35 +36 54 17.83 | 17.41 ± 0.03 | 1.06 |
| 6C1204+35    | 12 07 31.84 +35 03 07.01 | 17.82 ± 0.05 | 1.37 |
| 6C1217+36    | 12 20 09.79 +36 29 06.92 | 17.06 ± 0.03 | 1.00 |
| 6C1250+36    | 12 59 06.07 +36 31 58.52 | 17.15 ± 0.06 | 1.13 |
| 6C1257+36    | 12 59 30.22 +36 17 05.77 | 17.49 ± 0.06 | 1.00 |
| 6C18+8       | 02 07 34.97 +31 52 08.66 | 16.77 ± 0.02 | 1.21 |
times and seeing FWHM (as estimated using stars on the reduced images) for each image.

3 DATA ANALYSIS AND GALAXY DETECTION

After initial image processing using the IRAF package (see Eales et al. 1997), the Starlink PISA (Position, Intensity and Shape Analysis) package, developed by M. Irwin, P. D raper and N. E aton, was used to detect and catalogue the objects in each field. Objects were detected on the basis that they exceed a detection threshold of 1.5σ above the sky background (where the sky noise σ is separately determined by PISA for each of the images) in the least six connected pixels, and their fluxes were measured using the ‘total magnitudes’ option within PISA, which counts photons above the sky background level in elliptical apertures, fitted by a asymptotic curve-of-growth analysis to the intensity profile of each individual detection.

Observations of K-band standard stars provided a photometric zero-point of K = 21.28 for 1 count s⁻¹. However, due to the offset between the K and K’ passbands, this zero-point will be exact only for objects with the same K’ – K as the standard stars. Radio galaxies with elliptical-like colours will at 1 ≤ z ≤ 1.4 be redder than the calibration stars by an estimated Δ(K’ – K) = -0.13 mag (see Eales et al. 1997), so to correct for this we add Δ(K) = -0.13 mag to all magnitudes by adopting a zero-point of K = 21.15 for 1 count s⁻¹.

PISA also produces a list of eight areas for each detected object. The first area is simply the number of pixels where the intensity equals or exceeds the chosen detection threshold 1.5σ (for 2 ≤ 8 are the areas above higher thresholds of I₄σ + 2I₂σ + 2I₀σ, where j is an integer from 2 to 8. For these images, I₄σ = 50 counts, so the 8th threshold would be ∼ 1074 counts and ∼ 7.5 mag above the detection threshold.

We are concerned here only with the radio galaxies; the properties (e.g., clustering) of the other galaxies on these images will be discussed in a separate paper. Figs 1 and 2 show grey-scale images and contour plots of 15 × 15 arcsec² areas centred on each radio galaxy. Table 1 lists the K-band total magnitudes of the radio galaxies, as measured from these data (with errors estimated from the best-fitting models described in Section 4 below). These are consistent with the K magnitudes of Eales et al. (1997). Table 2 lists the 1.5σ detection thresholds of the images in terms of K mag arcsec⁻².

When PISA is run with the deblend option, two of the radio galaxies are detected as double objects, namely 6C 1011 + 36 with components of 1.7-arcsec separation and 6C 1256 + 36 with components of 2.5-arcsec separation. These double objects are still connected at the detection threshold, so they are split only when PISA is run with the deblend option. In this analysis we have used PISA without deblending, so these galaxies are detected as single objects and our derived magnitudes and areas will be those of both components added together. The 6C 1129 + 37 galaxy is also visibly bimodal, but the peaks are not so strongly separated and it was detected by PISA as a single object.

4 ESTIMATING GALAXY SIZES AND PROFILES

4.1 Method

Most of the radio galaxies appear extended on these images. To estimate their intrinsic angular sizes and distinguish between disc and bulge profiles, we compare their areas above thresholds (Section 3) with those measured by PISA for simulated galaxy profiles. We consider three types of source profile.

(i) A point source.
(ii) An exponential disc, with surface brightness $\mu \propto \exp(-r/r_{\text{exp}})$. We consider exponential scale lengths in the range $0.07 \leq r_{\text{exp}} \leq 1.00$ arcsec. The half-light radius $r_{\text{hl}} = 1.68 r_{\text{exp}}$.
(iii) A bulge (elliptical galaxy) profile, with surface brightness $\mu \propto \exp(-7.67(t/r_e)^{0.25})$. We consider effective radii (r_e) in the range $0.07 \leq r_e \leq 3.00$ arcsec. For this profile $r_{\text{hl}} = r_e$.

Each model profile was generated on a 0.1-arcsec pixel grid, and then rebinned into 0.5-arcsec pixels. The modified profiles were arranged in a grid pattern on a ‘simulation image’, with each model profile represented 12 times with slightly different positional offsets relative to the 0.5-arcsec pixel grid. The seeing profile was estimated for each image by fitting (using a PISA routine) a combined Gaussian-exponential-Lorentzian to objects identified as stars (of similar apparent magnitude to the radio galaxies). The simulation image was then convolved with the model stellar profile and normalized so that the model profiles had the same total intensity as measured for the radio galaxy. Gaussian noise was then added to the simulation image, with σ equal to the sky noise as measured on the real data.

The simulation image was then analysed using PISA, with the same detection threshold as used for the radio galaxy data. For each model profile, this gave 12 sets of areas above the eight thresholds, with some scatter between the 12 due to the modelled sky noise and the positional offsets between the models. These 12 sets of areas were averaged to give a set of eight PISA areas corresponding to each model profile, with error bars calculated from the scatter. For each radio galaxy we then compared the observed set of eight areas with those measured for each of the models, using a $\chi^2$ test with the simulation errors.

Table 3 shows the results of this comparison for each object, with $\chi^2$ for the point-source models, the exponential

Table 2. The total exposure times, seeing FWHM and 1.5σ detection thresholds of the Redeye images.

| Radio galaxy | Exposure time (minutes) | Seeing FWHM (arcsec) | Detection threshold $K$ mag arcsec⁻² |
|--------------|-------------------------|----------------------|-------------------------------------|
| 6C0822+39    | 31                      | 0.86                 | 21.88                               |
| 6C0943+39    | 30                      | 1.04                 | 22.09                               |
| 6C1011+36    | 45                      | 1.38                 | 21.96                               |
| 6C1017+37    | 26                      | 1.44                 | 22.09                               |
| 6C1123+34    | 45                      | 1.32                 | 22.66                               |
| 6C1129+37    | 47                      | 1.07                 | 22.04                               |
| 6C1204+35    | 42                      | 1.24                 | 22.32                               |
| 6C1217+36    | 27                      | 1.24                 | 22.21                               |
| 6C1256+36    | 42                      | 1.22                 | 22.15                               |
| 6C1257+36    | 22                      | 1.28                 | 21.97                               |
| 5C9.8        | 67                      | 1.38                 | 22.48                               |
Figure 1. Grey-scale plots of 15 × 15 arcsec² areas of the K′-band Redeye images centred on each radio galaxy. North is at the top, east at the left. Top row (left to right): 6C 0822 + 39, 0943 + 39 and 1011 + 36. Second row: 6C 1017 + 37, 1123 + 34 and 1129 + 37. Third row, 6C 1204 + 35, 1217 + 36 and 1256 + 36. Bottom row: 6C 1257 + 36 and 5C 6.8.
Figure 2. Contour plots of the images in Fig. 1, with contours at 1.0-mag intervals of surface brightness.

Table 3. The observed central surface brightness of the radio galaxies, and a comparison of their areas above a series of eight thresholds with those of model profiles: (i) the $\chi^2$ for a point-source model; (ii) the $\chi^2$ and exponential scalelength (with $\pm 1\sigma$ errors) of the best-fitting disc-profile model; (iii) the $\chi^2$ and effective radius (with $\pm 1\sigma$ errors) of the best-fitting bulge-profile model.

| Radio galaxy | Central SB K mag arcsec$^{-2}$ | Point Source model $\chi^2$ | Best-fit Disk model $r_{\text{exp}}$ (arcsec) $\chi^2$ | Best-fit Bulge model $r_e$ (arcsec) $\chi^2$ |
|--------------|-------------------------------|----------------------------|-----------------------------------------------|-----------------------------------------------|
| 6C0822+39    | 18.49 ± 0.17                  | 2595.7 ± 128.6             | 0.45$^{+0.13}_{-0.02}$ 90.9 ± 19.0 0.83$^{+0.10}_{-0.06}$ 11.4 ± 12.7     |
| 6C0943+39    | 19.08 ± 0.21                  | 175.2 ± 23.9               | 0.14$^{+0.04}_{-0.03}$ 25.2 ± 14.5 0.27$^{+0.33}_{-0.14}$ 18.9 ± 9.1      |
| 6C1011+36    | 18.81 ± 0.16                  | 118.5 ± 17.4               | 0.11$^{+0.03}_{-0.04}$ 19.0 ± 8.0  0.19$^{+0.09}_{-0.11}$ 19.5 ± 10.2   |
| 6C1017+37    | 19.80 ± 0.12                  | 20.5 ± 6.3                 | 0.10$^{+0.02}_{-0.03}$ 11.7 ± 7.4  0.12$^{+0.19}_{-0.06}$ 14.5 ± 8.6      |
| 6C1123+34    | 19.29 ± 0.06                  | 357.6 ± 52.4               | 0.32$^{+0.02}_{-0.03}$ 20.6 ± 11.8 0.27$^{+0.19}_{-0.03}$ 14.5 ± 15.1    |
| 6C1129+37    | 19.56 ± 0.14                  | 1316.1 ± 123.8             | 0.46$^{+0.02}_{-0.02}$ 4.0 ± 9.1  0.66$^{+0.07}_{-0.09}$ 57.4 ± 12.2    |
| 6C1204+35    | 19.07 ± 0.06                  | 201.0 ± 38.6               | 0.28$^{+0.04}_{-0.06}$ 14.1 ± 9.9  0.51$^{+0.10}_{-0.14}$ 5.8 ± 9.1       |
| 6C1217+36    | 18.48 ± 0.12                  | 292.2 ± 54.7               | 0.28$^{+0.04}_{-0.05}$ 45.8 ± 19.1 0.44$^{+0.18}_{-0.20}$ 11.4 ± 11.3     |
| 6C1256+36    | 19.04 ± 0.09                  | 2075.7 ± 111.1             | 0.63$^{+0.06}_{-0.07}$ 69.6 ± 21.5 0.98$^{+0.04}_{-0.02}$ 85.5 ± 21.7     |
| 6C1257+36    | 19.10 ± 0.11                  | 460.1 ± 37.2               | 0.28$^{+0.04}_{-0.05}$ 20.5 ± 11.9 0.37$^{+0.07}_{-0.08}$ 9.5 ± 11.7      |
| 5C6.8        | 18.13 ± 0.05                  | 233.8 ± 35.1               | 0.09$^{+0.02}_{-0.01}$ 46.0 ± 20.3 0.09$^{+0.02}_{-0.01}$ 43.4 ± 15.9     |
scalelength ($r_{\text{exp}}$) and $\chi^2$ of the disc-profile model which best fits the observed set of eight areas (i.e., which gives the smallest $\chi^2$), and the effective radius ($r_e$) and $\chi^2$ of the best-fitting bulge model.

For a $\chi^2$ test with 7 degrees of freedom, we would expect a 'perfect' model to give, on average, $\chi^2 \approx 6.4$, and would estimate $\pm 1\sigma$ errors on $r_{\text{exp}}$ and $r_e$ as the change in the model radius above or below the best-fitting model which increases $\chi^2$ by 8.16 above its minimum value. However, in this analysis the eight areas given by PISA are not entirely independent; a large noise fluctuation could change a pixel's value by more than one threshold interval, thus altering more than one of the areas. To take this into account, we also $\chi^2$-test the observed areas above thresholds against each of the 12 representations of the best-fitting model in our simulation image, obtaining 12 values of $\chi^2$. The scatter in these 12 values of $\chi^2$ gives the $\pm 1\sigma$ errors (listed in Table 3) produced by noise on the best-fitting model's $\chi^2$. The errors on the best-fitting $r_e$ and $r_{\text{exp}}$ can be estimated as the change in these radii which increases $\chi^2$ above that of the best-fitting model by these $1\sigma$ noise errors.

The true errors on the size estimates may be even larger due to other contributions. These include the following.

(i) Inaccuracy in the measurement of the point spread function. However, seeing profiles fitted to the data without further corrections.

(ii) Asymmetry and substructure in the real radio galaxies. However, the fact that we generally obtain similar estimates of the $r_{\text{exp}}$ for exponential and bulge models suggests that the $r_{\text{exp}}$ estimates are not very sensitive to galaxy morphology at least for galaxies consisting primarily of extended exponential or bulge components or combinations of the two (as opposed to point sources).

It is likely that the dominant source of error in estimating $r_{\text{exp}}$ is the sky noise in the galaxy images. As this is fully taken into account in our modelling, we give the model errors without further corrections.

However, our method will certainly underestimate $r_e$ and its associated error for galaxies with bright point-source components. To estimate the likely effect of point sources, we consider a bulge-profile model with $r_e=1.8$ arcsec – the mean size of the Best et al. (1998) 3CR galaxies – to which is added a central point source contributing from 0 to 100 per cent of the total flux. These models were convolved with typical seeing profiles, normalized to $K=17.4$, combined with sky noise typical of the real data, and then analysed in the same way as the real radio galaxy images. Fig. 3 shows the estimated bulge-model $r_e$ as a function of the point-source contribution to the total flux. A point-source component of 10 per cent reduces the fitted $r_e$ by $\approx 25$ per cent. As only 2/21 of the nine 1 radio galaxies of Best et al. (1998) had point-source components of $\geq 10$ per cent in the K-band, it seems unlikely that the effect of point sources on our $r_e$ estimates will be any larger than this (except in the case of the QSO), but we discuss this further in Section 7.

4.2 Results

First, the point-source models are generally a poor fit, giving a large $\chi^2$. Using the estimated noise errors on $\chi^2$, we can quantify the rejection of a point-source profile as $\sim 2\sigma$ for 6C 1017 + 37, but $\sim 6$–$20\sigma$ for the other nine radio galaxies. Even for the QSO, a pure point source is rejected by $6.7\sigma$. For all objects except 6C 1256 + 36 and the QSO, there is a disc model and/or a bulge model with a $\chi^2$ sufficiently low to indicate consistency within $2\sigma$. In some cases, $\chi^2$ is very similar for the best-fitting disc and bulge models; for other galaxies one model may be favoured by as much as several $\sigma$.

Fig. 4 shows histograms of the areas of each radio galaxy above the eight thresholds, together with the areas derived from the point-source model and the best-fitting disc and bulge models. To compare the models and data more directly, we also show radial intensity profiles. Fig. 5 shows the mean K-band intensity in $\Delta(r)=0.5$ arcsec annuli about the centroid of each radio galaxy, together with the point-source profile and the best-fitting disc and bulge models. Table 3 lists the apparent surface brightness (SB) of each galaxy within the central 0.5 arcsec. A slight difference in intrinsic SB will be partially obscured by the effects of seeing, we do see a difference in apparent SB between the different types of galaxy. For the 10 6C galaxies, the mean apparent central SB is $19.07 \pm 0.13$ K mag arcsec$^{-2}$, but that of the QSO is significantly higher, and the SBs of the galaxies 6C 1017 + 37 and 1129 + 37 are particularly low. The morphologies of the individual galaxies are described below.

5 MORPHOLOGY OF INDIVIDUAL RADIO GALAXIES

1. 6C 8022 + 39 appears symmetric with a profile well fitted by the bulge model, which is strongly ($\sim 4\sigma$) favoured over a disc model. This galaxy appears in the K band to be a normal elliptical.

2. 6C 0943 + 39 is a small symmetrical object, consistent with either disc or bulge at the $1\sigma$ level. On the basis of these data, it could be another normal elliptical.
3. 6C 1011 + 36 is small and asymmetric, with a much fainter secondary nucleus 1.7 arcsec from the main nucleus but clearly within the outer envelope, suggesting that it is currently merging with a much smaller galaxy. It may also be interacting with two close companions, which produce the peak in the profile at $r \sim 4$ arcsec. Neither a disc nor a bulge profile is strongly favoured.

4. 6C 1017 + 37 is another small symmetric object, apparently the smallest of these galaxies. It is consistent with either disc or bulge models at the 1$\sigma$ level, and the only galaxy consistent at the $<3\sigma$ level with being a point source. The low central SB is presumably due to the object being faint and unresolved, rather than being an intrinsically low-SB galaxy. There is no excess above the fitted models at either small or large radii, so this object could simply be a small elliptical.

5. 6C 1123 + 34 is round and symmetric, with a profile consistent with both the disc and bulge models. There is another galaxy about 5.5 arcsec away, but no obvious indication that the two are interacting. This could be a normal elliptical.

6. 6C 1129 + 37 is extended and asymmetric with two intensity peaks of similar luminosity. These lie well within a common envelope, so that PISA detects 6C 1129 + 37 as a single large galaxy even with the deblend option. The outer regions appear disturbed with some evidence of trails, especially to the north. This is the only galaxy in this sample for which the profile appears to significantly ($\sim 4\sigma$) favour an exponential model over a bulge model. It also has a low central SB (0.49 mag less than the sample mean) which, as the galaxy is clearly resolved, would imply that the intrinsic central SB is lower than that of the other radio galaxies. A recent red-band WFPC2 image of this galaxy, to be described by Best et al. (in preparation), also showed the following.

(i) The two peaks seen in the K image (centroids separated by 1.9 arcsec) lie within elongated structures with tails pointing inwards to the galaxy centre, suggesting that they are ‘hotspots’ associated with the outward passage of the radio jets rather than the two components of a merger. Close to the centre the jets appear to be aligned with the 137° position angle of the two peaks of radio emission (Allington-Smith 1982; Eales et al. 1997), although the two radio lobes lie much further out, being separated by 14 arcsec. Further out from the centre, the R-band jets curve...
slightly towards an east–west axis, causing the K-band peaks to be slightly misaligned from the radio axis.

(ii) The faint extension to the north is a small spiral galaxy of high R-band ($\lambda_{\text{rest}} \approx 3000$ Å) SB, which appears to be interacting with the larger radio galaxy. Allington-Smith et al. (1982) had previously found 6C 1129 + 37 to be double on a ground-based R-band CCD image, with the two components separated north–south, so presumably corresponding to the radio galaxy and this companion rather than the two radio jet hotspots.

(iii) No central point source is visible at $\lambda_{\text{rest}} \approx 3000$ Å.

7. 6C 1204 + 35 appears symmetric, slightly favouring ($\sim 1\sigma$ level) a bulge over a disc profile. There is no excess above the fitted bulge model at large radii. This galaxy seems consistent with being a normal elliptical.

8. 6C 1217 + 36 is extended, with a bulge profile favoured over an exponential disc by $\sim 2\sigma$. The outer regions look slightly asymmetric, with some isophotal twist apparent on the contour plot. The radial profile is very close to the bulge model, except for a small excess at $r \sim 5$ arcsec due to a much smaller companion galaxy. This could, for example, be a normal elliptical slightly perturbed by a near-miss encounter, resulting in a slight asymmetry.

9. 6C 1256 + 36 is extended and double with a less luminous secondary nucleus. 2.5 arcsec from the main nucleus. The outer regions are asymmetric and much more extended than in the other double galaxy (6C 1011 + 36), with the second nucleus lying within what appears to be an inclined disc. The galaxy may also be interacting with its much smaller nearby companion (there is a hint of a bridge between the two). The galaxy is not well fitted by either a disc or a bulge model, having too much area at the lowest thresholds. However, the radial profile looks closer to the bulge model at $r < 2$ arcsec, and the central SB is typical of this sample (in contrast to 6C 1129 + 37), suggesting that the primary galaxy is an elliptical. This is consistent with the visual impression of an elliptical merging with a large, lower SB disc galaxy.

10. 6C 1257 + 36 is closer to a bulge profile than a disc, though only by $\sim 1\sigma$. The profile is well fitted by the bulge model, except for an excess at $r \sim 4$ arcsec due to a small companion galaxy. This galaxy could be another normal elliptical.

11. The QSO 5C 6.8 contains a very bright central nucleus, giving a central SB higher than that of any of the 10 radio galaxies, and a very small $r_{\text{HL}}$. However, the object is not a pure point source. The K-band image also shows the
extended, lower surface brightness host galaxy, which appears disturbed, suggesting a recent merger or interaction. The profile is close to the fitted models at r < 3 arcsec, but shows a significant excess at r = 4 arcsec, where it resembles the more extended profiles of the radio galaxies. Consequently, neither the disc nor the bulge model is a good fit, and a pure point-source model is also rejected. Two-component models and higher resolution data would be needed to investigate systems of this type, by separately estimating the point-source contribution and an r$_{hl}$ for the underlying galaxy (see Best et al. 1998).

Even at this long wavelength of observation, these galaxies show evidence of diversity in their morphologies. Two galaxies, 6C 1011 + 36 and 1256 + 36 appear to be merging doubles, and are classed here as ‘mergers’. The 6C 1129 + 37 galaxy is the only object in the sample with radio jet features bright enough to be seen in these K-band images, so it is placed here in a separate class as a ‘radio jet object’.

Dunlop & Peacock (1993) and Ridgway & Stockton (1997) found that many z ~ 1 3CR galaxies do show an alignment between their K-band isophotes and radio axes, although no alignment was seen for Parkes radio galaxies an order of magnitude less radio-luminous. A study of this 6C sample is intermediate in radio luminosity, it is not altogether surprising that some of these galaxies appear to be more complex in structure than simple ellipticals, and we might have expected to find at least one galaxy with visible K-band radio alignment. The 6C 1129 + 37 galaxy appears to be the only galaxy of these 10 with resolved aligned features, but it may also be significant that 6C 0943 + 16.5 Gyr ago, and decreases rapidly with an exponential time-scale t$_{exp}$ = 0.5 Gyr. As almost all star formation occurs at z > 3, the evolution is passive at the redshifts we are concerned with here. This star formation history is converted into an evolving spectral energy distribution using an updated (‘BC96’; see, e.g., Leitherer et al. 1996) version of the Bruzual & Charlot (1993) models, with solar metallicity and a Salpeter IMF. Fig. 6 shows the R$_{rest}$ – K$_{obs}$ correction, as a function of redshift, derived from this model’s evolving spectral energy distribution, and from a much bluer model in which star formation begins at the same epoch but continues at a constant rate.

A at z = 1.1, the constant-SFR model predicts much bluer observer frame colours than the E/S0 model, R – K = 3.3 compared to R – K = 5.8, but the R$_{rest}$ – K$_{obs}$ corrections differ much less, by 0.38 mag. At z ~ 1.1, many radio galaxies have R – K colours close to a passively evolving model, which essentially defines the red envelope of their colour-redshift distribution, but some of the more radio-luminous (i.e., 3CR) galaxies are as much as ~ 2 mag bluer, with colours approaching a constant-SFR model (Lilly & Longair 1984; Dunlop & Peacock 1993). Hence an assumption an E/S0 model should give a conservative estimate of M$_{r}$, accurate for the redder galaxies but an underestimate by up to 0.38 mag for any objects which are as blue as the bluest 3CR galaxies.

Table 4 gives our estimates of M$_{r}$. All of these 6C galaxies are more luminous than the zero-redshift L* (M$_{r}$ ≈ –22.57 for ellipticals), with a mean M$_{r}$ for the radio galaxies (excluding the QSO) of –24.09 ± 0.18. To investigate the M$_{r}$ – r$_{hl}$ relation, we adopt the disc model size estimate, r$_{hl}$ = 1.68r$_{min}$ for all objects with a smaller minimum r$_{hl}$ estimates.

Figure 6. Modelled magnitude correction between the observer frame K band and rest frame Cousins R band, as a function of redshift, for a passively evolving E/S0 galaxy model and a model with a constant star formation rate.
by PISA. We therefore correct the $r_{hl}$ estimates for inclination by multiplying by $(1 - e)^{-0.5}$. Table 4 gives the ellipticities and corrected $r_{hl}$ estimates, again with $\pm 1\sigma$ errors, both in arcsec and in kpc for the assumed cosmology. The unweighted mean of the $r_{hl}$ estimates for the radio galaxies (excluding the QSO) is $6.1 \pm 1.3$ kpc.

**Table 4.** Estimated absolute magnitude of the radio galaxies in the rest frame $R$ band, the ellipticity of their images, and the half-light radius of the best-fitting model (with $\pm 1\sigma$ errors), corrected for inclination.

| Radio galaxy | Absolute $R$ Magnitude | Ellipticity | Estimated $r_{hl}$ |
|--------------|------------------------|-------------|--------------------|
|              |                        |             | arsec                     | kpc                     |
| 6C0822+39    | -24.87                 | 0.16        | $0.91^{+0.21}_{-0.06}$  | $10.1^{+2.4}_{-3.0}$   |
| 6C0943+39    | -23.50                 | 0.28        | $0.32^{+0.39}_{-0.17}$  | $3.4^{+4.1}_{-1.8}$    |
| 6C1011+36    | -23.74                 | 0.37        | $0.24^{+0.06}_{-0.08}$  | $2.5^{+0.6}_{-0.8}$    |
| 6C1017+37    | -22.93                 | 0.09        | $0.18^{+0.09}_{-0.04}$  | $1.9^{+0.6}_{-0.4}$    |
| 6C1123+34    | -24.24                 | 0.08        | $0.28^{+0.19}_{-0.3}$   | $3.1^{+2.1}_{-0.3}$    |
| 6C1129+37    | -24.18                 | 0.29        | $0.90^{+0.4}_{-0.04}$   | $9.7^{+0.4}_{-0.4}$    |
| 6C1204+35    | -24.54                 | 0.10        | $0.54^{+0.14}_{-0.09}$  | $6.2^{+1.6}_{-1.4}$    |
| 6C1217+36    | -24.37                 | 0.16        | $0.48^{+0.20}_{-0.22}$  | $5.1^{+0.4}_{-0.4}$    |
| 6C1256+36    | -24.61                 | 0.24        | $1.21^{+0.12}_{-0.14}$  | $13.4^{+1.3}_{-1.3}$   |
| 6C1257+36    | -23.94                 | 0.11        | $0.39^{+0.07}_{-0.08}$  | $4.2^{+0.7}_{-0.9}$    |
| 5C6.8        | -25.18                 | 0.11        | $0.09^{+0.10}_{-0.01}$  | $1.1^{+0.2}_{-0.1}$    |

**Figure 7.** Estimated half-light radius (in kpc) against rest frame $R$-band absolute magnitude for the 6C radio galaxies, with symbols indicating morphological classes assigned in Section 5, together with the 3CR radio galaxies from Best et al. (1998), the low-redshift FRII galaxies from Owen & Laing (1989), and $r_{hl}$–$M_R$ relations for local ellipticals (dashed line) and spirals (dotted line).
at $z > 0.93$, with a mean redshift ($z_{\text{mean}} = 1.10$) almost identical to that of our 6C sample, $z_{\text{mean}} = 1.11$ and the 12 at $z < 0.93$, with $z_{\text{mean}} = 0.73$. The absolute magnitudes of the 3CR galaxies were estimated using the K-band aperture magnitudes of Lilly & Longair (1984), extrapolated to total magnitudes assuming bulge profiles with $r_e$ from Best et al. (1998), and adopting the same E/S0 model $R_{\text{rest}} - K_{\text{rest}}$ correction as used for the 6C galaxies.

The 3CR galaxies are, on average, more luminous (mean $M_R = -24.72 \pm 0.15$) and much larger (mean $r_\text{e} = 17.9 \pm 1.5$ kpc) than the 6C galaxies. The 3CR galaxies at $0.93 < z < 1.27$ are more luminous (mean $M_R = -25.14 \pm 0.16$) than those at $0.47 < z < 0.93$ (mean $M_R = -24.40 \pm 0.20$, but not significantly different in size (mean $r_\text{e} = 17.5 \pm 1.7$ kpc compared to $18.2 \pm 2.4$ kpc). The 3CR galaxies at $0.93 < z < 1.27$ are, on average, $1.05 \pm 0.24$ mag more luminous in the R band, and $0.46 \pm 0.6$ larger, than our 6C galaxies at the same redshift (note that this result will not depend significantly on the assumed $q_0$). This magnitude difference is greater than the 0.7 mag reported by Eales et al. (1997) for a $z > 0.6$ sample, probably as a result of our exclusion of the less evolved 3CR galaxies at $0.6 < z < 0.93$ and our use of total rather than metric magnitudes (giving a greater difference in luminosity between small and large galaxies).

To compare these galaxies with those at lower redshift, Fig. 7 shows local $r_e - M_R$ relations, converted from the $r_e - M_R$ relations (used, by e.g., Roche et al. 1998) to the R band assuming $z = 0$ colours of B - R = 1.50 for ellipticals (as given by the model) and B - R = 1.0 for spirals. For ellipticals, the Bingelli, Sandage & Tarenghi (1984) relation becomes

$$\log(r_{e}/\text{kpc}) = -0.3(M_R + 20.07)$$

for $M_R < -21.5$, and

$$\log(r_{e}/\text{kpc}) = -0.1(M_R + 17.20)$$

for $M_R > -21.5$.

For spirals, the Freeman (1970) surface brightness becomes

$$\log(r_{e}/\text{kpc}) = -0.2M_R - 3.42.$$  

Owen & Laing (1989) estimated absolute magnitudes in the Cousins R band and bulge-model-fitted radii for $z < 0.2$ radio galaxies of a number of types. In Fig. 7 we plot their classical double FRII (Fanaroff & Riley 1974) radio galaxies, the type most appropriate for comparison with the higher redshift samples, with sizes and magnitudes converted to $H_\alpha = 50$ km s$^{-1}$ M pc$^{-1}$ and isophotal $M_R$ extrapolated to total magnitudes assuming bulge profiles with the fitted effective and isophotal radii. These 24 low-redshift ($z_{\text{mean}} = 0.11$) radio galaxies are less luminous (mean $M_R = -23.37 \pm 0.12$) than those at higher redshift, and have a very wide range of sizes with a mean $r_e$ of $12.5 \pm 2.3$ kpc, intermediate between the 6C and 3CR galaxies.

The QSO 5C 6.8 is displaced far from the other sources in this plot, on account of its K-band flux being dominated by a central point source. As our method is not valid for measuring the true galaxy size of this object, it is excluded from the following discussion of $r_e - M_R$ relations.

The 6C galaxies are clearly shifted relative to the $r_e - M_R$ relation of local ellipticals, in the direction of a higher intrinsic SB. As noted by Best et al. (1998), the 3CR objects also tend to be enhanced in SB relative to local ellipticals. Note that estimates of the intrinsic SB will be independent of the assumed $q_0$ and $H_\alpha$. The $r_e - M_R$ relations of both the $z = 0$ and the $z \sim 1$ radio galaxies are noticeably steeper than the $\Delta(\log(r_e)) = -0.2\Delta(M_R)$ slope of constant SB typical of spirals and are more consistent with the $\Delta(\log(r_e)) = -0.3\Delta(M_R)$ slope of the giant ellipticals. Hence, to estimate the surface brightness evolution $\Delta R$ relative to local E/S0 galaxies of the same size, we fit the function

$$\log(r_{e}/\text{kpc}) = -0.3(M_R + \Delta R + 20.07).$$

For the seven 6C galaxies we classed as bulge/generic types, $\chi^2$ is minimized for $\Delta R = 1.58 \pm 0.22$ mag, with a $\chi^2$ of only 6.8 indicating that all seven are consistent with this single $r_e - M_R$ relation. One of our double objects (6C 1011 + 36) lies on the same relation. It appears to be undergoing just a minor merger, of a large elliptical with a much less massive dwarf galaxy, and this might not greatly affect the total size or luminosity. However, the other double object (6C 1256 + 36) and the ‘radio jet’ galaxy 6C 1129 + 37 are of lower mean SB, corresponding to $\Delta R = 0.79 \pm 0.27$ and $0.82 \pm 0.12$ mag respectively. The image of 6C 1256 + 36 is suggestive of an elliptical merging with a large, low-SB disc galaxy. This would obviously decrease the mean SB of the combined object and give it a more disc-like profile, while accounting for the central SB remaining high. In contrast, the radio jet object 6C 1129 + 37 has an intrinsically low central SB as well as a low mean SB. A non-weighted fit to all 10 6C objects gives $\Delta R = 1.03 \pm 0.17$ mag, but with a high $\chi^2$ of 63.7 indicating that the galaxies are not all consistent with a single $r_e - M_R$ relation - there is a significant difference between the two relatively low mean SB objects and the relation defined by the other eight objects.

An unweighted fit of the same relation to the 24 FRII galaxies at $z < 0.2$ gives $\Delta R = 0.06 \pm 0.19$ mag, consistent with unevolved ellipticals. An unweighted fit to the 21 3CR galaxies gives an evolution of $\Delta R = 0.58 \pm 0.15$ mag, rather less than that for our sample. However, the lower redshift (0.47 < $z$ < 0.92) 3CR subsample gives $\Delta R = 0.28 \pm 0.18$, while the higher redshift (0.92 < $z$ < 1.27) 3CR subsample gives $\Delta R = 0.98 \pm 0.18$. There appears to be significant SB evolution of 0.70 \pm 0.25 mag between the respective mean redshifts of 0.73 and 1.10. The higher redshift 3CR subsample is much closer in its size–luminosity relation to the 6C galaxies at $z_{\text{mean}} = 1.11$. We discuss the implications in Section 7 below.

7 DISCUSSION

7.1 Surface brightness evolution

Using ground-based data, we have carried out a preliminary investigation of the K-band angular size and morphology of 6C radio galaxies at 1 < $z$ < 1.4. Our first result is that the 6C galaxies typically have smaller K-band half-light radii than 3CR radio galaxies at similar redshifts. This appears to exclude the hypothesis that 3CR and 6C sources at $z \sim 1$ have identical host galaxies, and that the higher K-band
luminosity of the 3CR sources (e.g. Eales et al. 1997) is due solely to their more powerful active nuclei. If this was the case, the 3CR galaxies would have smaller half-light radii than their 6C counterparts, due to the greater dominance of the central point sources. The difference in K luminosity appears to be due primarily to the stellar components, which in the 3CR galaxies are considerably larger and presumably more massive.

We estimate that the $z_{\text{mean}} = 1.11$ 6C galaxies show a mean surface brightness enhancement of $1.03 \pm 0.17$ mag in the rest frame Cousins R band, relative to the $r_m - M_\odot$ relation of local ellipticals. This is very much consistent with the 0.98 $\pm$ 0.18 mag of SB evolution we estimate for a subsample of more radio-luminous 3CR galaxies at the same mean redshift. The 6C galaxies which most resembled normal ellipticals appeared to show greater SB evolution of $1.58 \pm 0.22$ mag. This may be an overestimate if they contain central point sources. We estimated (Section 4.1) that a central point source contributing 10 per cent of the K-band flux from a galaxy could reduce our estimated $r_m$ by 25 per cent, which would increase the estimated $\Delta r$ by 0.42 mag.

However, it is very unlikely that the presence of point sources can make more than a small contribution to the much larger difference between 6C and 3CR galaxies in the estimated radii. To reduce the fitted $r_m$ from 1.8 arcsec, the mean size of the 3CR galaxies, to 0.55 arcsec, the mean size of the 6C galaxies, would require a much larger point-source contribution of $\geq 30$ per cent. Although we are at present only able to exclude a strong central point source in the case of 6C 1129 + 37 (for which we have WFPC2 data), only 2/21 of the 3CR galaxies of Best et al. (1998) had profiles consistent with point-source components of $\geq 10$ per cent in the K band, and if anything the less radio-luminous 6C galaxies would be expected to show less nuclear activity. If point sources are present in the bulge/generic galaxies at the 0–10 per cent level, they must still be showing at least $\sim 1.16$ mag of genuine SB evolution. This is less than the SB enhancement of $\sim 3$ galaxies in the Hubble Deep Field (e.g.) ones & Disney 1996; Roche et al. 1998), so there is no doubt that this is physically possible for large galaxies at $z > 1$.

In contrast, the SB of FRII radio galaxies at $z_{\text{mean}} = 0.11$ showed only $0.06 \pm 0.19$ mag of evolution relative to the local elliptical $r_m - M_\odot$ relation, consistent with the 0.14 mag of passive evolution predicted by our model at their mean redshift. This confirms that the assumed $r_m - M_\odot$ relation is appropriate for powerful radio galaxies at low redshifts as well as for normal ellipticals, and hence that the $r_m - M_\odot$ relation of FRII radio galaxies in particular does shift with increasing redshift. This shift of the $r_m - M_\odot$ relation is very similar to that seen for normal radio-quiet ellipticals over a similar redshift range. Schade, Barrientos & López-Cruz (1997) found the rest frame blue-band SB evolution of a mixture of field and cluster ellipticals to be best fitted by 0.78z mag for $q_0 = 0.5$, or $\sim 0.92z$ mag for a low $q_0$. This is consistent with the passively evolving E/S0 model described in Section 6, which predicts $\Delta (M_\odot) = -0.93$ mag at $z = 1$. In the rest frame Cousins R band, the model predicts evolution of $\Delta (M_\odot) = -0.77$ mag, increasing to $\Delta (M_\odot) = -0.83$ mag at $z = 1.11$. Hence the rate of R-band SB evolution of both the 3CR and 6C galaxies appears consistent with, or if anything slightly faster than, that expected from passive stellar evolution models.

### 7.2 Implications for radio galaxy evolution

The simplest evolutionary scenario is that luminosity and SB change but $r_m$ does not. A though there is probably some increase with time in the mean size of galaxies, angular sizes from WFPC2 data suggest that, for ellipticals, this is a small effect out to $z \sim 1$ (e.g. Im et al. 1996; Roche et al. 1998).

Assuming no evolution in $r_m$, the estimated radii of the $z \sim 1.1$ 6C galaxies would on the basis of the assumed local $r_m - M_\odot$ relation indicate their local counterparts to have a mean absolute magnitude $M_\odot = -22.6$, i.e. about L*, and therefore suggest that many evolve into $L \sim L*$ ellipticals. Most of the z < 0.2 FRII radio galaxies in the Owen & Laing (1989) sample are ellipticals of modest size and $L \sim L*$ luminosity, although quite high radio luminosities of $L(1400 \ M Hz) \sim 10^{25.1}$ W Hz$^{-1}$. It is tempting to identify these as the low-redshift counterparts of our 6C galaxies. Their typical radio luminosity corresponds to $L(151 \ M Hz) \sim 10^{24.3}$ W Hz$^{-1}$ for the average spectral energy distribution of luminous radio galaxies ($z \sim -0.94$), so this would require a factor of $\sim 25$ decrease in radio luminosity since $z \sim 1.1$. This is consistent with the 6C radio luminosity function undergoing the same $\sim 3.3$ Gyr rate of evolution as estimated (Padovani & Urry 1992) for that of 3CR galaxies, but of course, if our identification is correct, the evolution of the radio luminosity function must be due to the evolution of individual objects rather than simply a change in the number of galaxies which become powerful radio sources.

Owen & Laing (1989) and Owen & White (1991) found that the classical double FRII radio galaxies at $z < 0.2$ were typically $\sim 10^{14}$ times higher in radio luminosity ($L_{\text{rad}}$) than FRI galaxies of similar optical luminosity, with the dividing line between the classes following a $L_{\text{rad}} \propto L_{\text{opt}}$ relation (Ledlow & Owen 1996). As previously reported by, e.g., Longair & Seldner (1979) and Prestage & Peacock (1989, 1989), the FRI radio galaxies tended to lie within clusters (on average A bell class 0), while nearby FRIIs were usually in field environments. However, Yates, Miller & Peacock (1989) and Hll & Lilly (1991) found that powerful radio galaxies at higher redshifts ($z \sim 0.5$) were as likely to lie in A bell class 0–1 clusters as in the field, suggesting a more rapid $L_{\text{rad}}$ evolution for the sources in clusters.

If any of these 6C galaxies lie in rich clusters, their low-redshift counterparts might instead be FRI galaxies, like the smaller of those in the Owen & White (1991) sample, with much lower present-day radio luminosities of $L(1400 \ M Hz) \sim 10^{14.7}$ W Hz$^{-1}$. This corresponds to $L(151 \ M Hz) \sim 10^{24.8}$ W Hz$^{-1}$, a factor of $\sim 1000$ down on the $L_{\text{rad}}$ of our 6C galaxies. Yee & Ellingson (1993) estimate that the optical luminosity evolution of AGN in rich cluster environments (A bell class $\sim 1$) is as rapid as $\tau = 1.0 \pm 0.2$ Gyr out to $z \sim 0.6$, but at higher redshifts it must be similar to other AGN. If this form of evolution is paralleled by the evolution of $L_{\text{rad}}$, it would predict a decrease in $L_{\text{rad}}$ of a factor of $\sim 1000$ since $z \sim 1.1$, exactly the amount required.

We estimate that the mean $M_\odot$ of 3CR and 6C galaxies at $z \sim 1.1$ differs by $1.05 \pm 0.24$ mag. The mean radius of the
3CR galaxies is much larger, and with no size evolution would correspond to low-redshift counterparts with $M_\text{r} = -24.2$, several L*. On this basis we suggest that the difference in 3CR and 6C luminosity at $\lambda_{\text{rest}} \sim 1 \mu \text{m}$ is due to a difference in the stellar masses of the host galaxies. As the radio luminosities differ by a factor of $\sim 6$, this suggests a correlation $L_{\text{rad}} \propto M_{\text{stellar}}$.

A positive scenario explaining these observations is as follows.

(ii) At $z \gtrsim 1$, the maximum radio luminosity is strongly correlated with the stellar mass of the host galaxy, approximately as $L_{\text{rad}} \propto M^2$. Physically, this could be related to the higher pressure of surrounding gas, and perhaps the more massive central black hole, in a more massive galaxy (see, e.g., Rawlings & Saunders 1991 and Eales 1992). At $z > 1$, many of the 3CR and 6C galaxies may be observed while close to this upper limit, with the 3CR galaxies typically being $\sim 2.5$ times more massive and hence $\sim 6$ times more radio-luminous.

(ii) High-redshift radio galaxies exist in a mixture of field and cluster environments. The peak $L_{\text{rad}}$ attained during subsequent bursts of radio emission decreases more rapidly for radio galaxies in a rich cluster environment (Yee & Ellington 1993). By $z \sim 0$, the cumulative effect of this environmental dependence amounts to a factor of $\sim 10^{14}$ in $L_{\text{rad}}$ between Abell class 0 environments and the field, obscuring the $L_{\text{rad}} \propto M^2$ correlation seen at $z \gtrsim 1$. However, as the cluster environment also influences the evolution of the radio morphology, a $L_{\text{rad}} \propto M^2$ correlation reappears when nearby radio galaxies are separated into FRI and FRII types (Loveday & O’wen 1996).

At any rate, the high surface brightness and relatively small size of the 6C galaxies seems to argue that their evolution, at both optical and radio wavelengths, is no less rapid than that of the 3CR galaxies. Although the K–z relation of 6C galaxies may have appeared consistent with no evolution (Eales et al. 1997), their $r_{hl} - M_{\text{r}}$ relation clearly is not. Of course, the results of this paper, being based on a small data set of marginally adequate depth and resolution, should be regarded as only preliminary. We intend to investigate these objects and other $z \sim 1$ radio galaxies further to better constrain their $r_{hl}$ and morphology, and separate bulge, disc, point-source and radio jet components.

8 SUMMARY OF MAIN CONCLUSIONS

(i) A sample of 6C radio galaxies at $1 < z < 1.4$, observed in the K band, shows significant morphological diversity. Two galaxies appear to be mergers, another has two bright peaks aligned with the radio jets and may be closer to an exponential than a bulge profile, but the other seven were more consistent with normal elliptical morphologies in the K band.

(ii) We estimate a mean half-light radius of $6.1 \pm 1.3 \text{kpc}$ for the 6C galaxies, similar to that of present-day $L \sim L^*$ ellipticals and significantly smaller than the $r_{hl}$ of the 3CR galaxies studied by Best et al. (1998). Central point sources can cause our method to underestimate the $r_{hl}$ of galaxies, but cannot account for the large difference between the mean angular $r_{hl}$ of the 6C and 3CR galaxies, 0.55 and 1.8 arcsec respectively, unless they contribute $\geq 30$ per cent of the flux of 6C galaxies. This seems unlikely on the basis of the absence of point sources above 10 per cent in 19/21 of the 3CR galaxies. We conclude from this that the higher $L_{\text{rad}} \sim 1 \mu \text{m}$ luminosity of 3CR relative to 6C galaxies at $z \sim 1.1$ must reflect a genuine difference in the sizes of the host galaxies, so is not solely due to a difference in the power of the central nuclei.

(iii) The size–luminosity relation of the 6C galaxies at $z \sim 1.1$ is offset from that of either local ellipticals or FRII radio galaxies at $z < 0.2$, indicating 1.0–1.6 mag of surface brightness evolution in the rest frame $R$ band. This is similar to the $R$-band surface brightness evolution seen for 3CR galaxies in the same redshift range.

(iv) The sizes of the 6C galaxies are consistent with their low-redshift counterparts being FRII radio galaxies like those studied by Owen & Laing (1989), a factor of $\sim 25$ lower in radio luminosity, suggesting radio luminosity evolution similar to the Padovani & Urry (1992) estimate for 3CR galaxies. A ny 6C galaxies which lie in clusters may undergo a much greater reduction in radio luminosity to become FRI objects.

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