The nature of the 3CR radio galaxies at $z \sim 1$

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Abstract

We present evidence that the 3CR radio galaxies at redshift $z \sim 1$ are already very massive, highly dynamically evolved galaxies, which lie at the heart of (proto-)cluster environments. Since nearby 3CR double radio sources are generally found in more isolated surroundings, the galactic environments of these galaxies must change dramatically with redshift. Therefore, the original 'uniform population, closed box' interpretation of the infrared K-magnitude vs redshift relationship no longer appears valid.

We propose a new interpretation: the powerful radio galaxies selected at high and low redshift have different evolutionary histories, but must contain a similar mass of stars, a few times $10^{11} M_\odot$, and so conspire to produce the 'passively evolving' K–z relation observed. We discuss this model in the context of the current understanding of powerful radio sources and, in light of this new model, we compare the K–z relation of the 3CR galaxies with those derived for lower power radio galaxies and for brightest cluster galaxies.

1 Introduction

The revised 3CR sample is a complete sample of the brightest extragalactic radio sources in the northern sky, selected at 178 MHz (Laing et al. 1983). The host galaxies of the nearby ‘classical double’, or FR II, radio sources in the sample are giant elliptical galaxies. The infrared K–magnitude vs redshift relation has been widely used as a tool for investigating the evolution with cosmic epoch of the stellar populations of luminous galaxies, since K–corrections, dust extinction corrections, and the effect of any secondary star formation are all relatively unimportant at near–infrared wavelengths. The remarkably small
scatter and slope of this relation for the 3CR radio galaxies is consistent with passive, ‘closed–box’ evolution of a single population of giant elliptical galaxies which formed at large redshift (see Figure 1), suggesting that the distant 3CR galaxies are precisely the same objects as nearby 3CR galaxies, but observed at an epoch when their stellar populations were younger (Lilly and Longair 1984).

We have selected an almost complete sample of 28 radio galaxies from the 3CR sample, with redshifts in the range $0.6 < z < 1.8$. These galaxies were observed for one orbit each in each of two colours (at rest–frame wavelengths of approximately 315 and 475 nm) using the HST, and for about an hour in the near–infrared J and K–bands using UKIRT, with 1 arcsecond angular resolution. A detailed description of the observations, and the reduced images, can be found in Best et al. (1997a).

2 The host galaxies of 3CR radio sources

2.1 The origin of the near–infrared emission

In 1987, McCarthy et al. and Chambers et al. discovered that the optical (rest–frame ultraviolet) emission of powerful distant radio galaxies is elongated and aligned along the direction defined by the radio lobes. The high resolution HST images of the 3CR galaxies show this clearly, with some galaxies having many bright optical knots strung along the radio jet axis (Best et al. 1997a). A number of models have been proposed for this ‘alignment effect’, the three most promising being jet–induced star formation (e.g. Rees 1989), scattering of light from an obscured quasar by electrons or dust (Cimatti et al. 1996 and references therein), and nebular continuum emission (Dickson et al. 1995). Some combination of all of these processes is most likely to be occurring. A complete discussion of these issues is not possible in the space available here, and can be found in many other contributions to this volume. It is important to note, however, that each of these alignment mechanisms produces relatively flat spectrum emission, and so in the K–band this aligned emission will be dominated by that of the old stellar population. Best et al. (1997b) showed that, on average, only about 10% of the K–band flux density of the 3CR radio galaxies at redshift one is associated with the aligned component.

An investigation of the infrared radial intensity profiles of these 3CR galaxies shows that, in general, they can be well–matched using de Vaucouleurs’ law, with little requirement for any contribution from unresolved nuclear emission. A detailed description of the fitting procedure can be found in Best et al. (1997b);
in Figure 2, we show examples of the fits for 12 of the galaxies. There is significant evidence for a contribution to the K–band flux density from an unresolved nuclear emission source in only two of the sources in the sample, 3C22 and 3C41, providing about 50% and 30% respectively of the K–band light in these

![Figure 1](image)

**Figure 1.** The K–z relation for 3CR radio galaxies (open triangles; from Lilly and Longair 1984, Best et al. 1997a), 6C radio galaxies (filled squares; from Eales et al. 1997), and brightest cluster galaxies (crossed circles; from Aragón–Salamanca et al. 1993). The data have been converted, where necessary, to a 63.9 kpc metric aperture ($H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$) using a radial light profile appropriate for low redshift giant ellipticals (Lilly et al. 1984). The solid and dashed lines show the relations expected for a non-evolving and passively evolving ($z_f = 5$) stellar populations respectively, derived using the stellar synthesis codes of Bruzual and Charlot (1993) and normalised to match the 3CR galaxies at low redshift. The vertical line at redshift $z \sim 0.6$ provides a useful division between the high and low redshift populations.
cases. Interestingly, Rawlings et al. (1995) have already proposed that 3C22 contains a reddened quasar, based upon the red colour of its spectral energy distribution and the detection of broad Hα emission. For the remaining sources in the sample, the best fit to the K–band radial profile has \( \lesssim 10\% \) of the total flux density associated with a point source component, and in each case this is consistent, within the 90% confidence limits, with being zero.

A third possible AGN–related contribution to the emission of these galaxies is line emission, but for the redshifts of the present sample there are no major emission lines in the K–band (Hα enters the passband beyond \( z \approx 1.9 \)), and so line emission contributes typically \( \lesssim 5\% \) of the K–band flux density. We conclude that the K–band flux density of the 3CR radio galaxies at redshift \( z \sim 1 \) is dominated by emission from their old stellar populations.

### 2.2 Fundamental parameters of the 3CR radio galaxies

The characteristic radii, \( r_e \), of the distant 3CR galaxies, as determined from the de Vaucouleurs fits, are generally large with a mean value of \( 14.6 \pm 1.4 \) kpc \((q_0 = 0.5)\). In terms of standard cannibalism models (e.g. Hausman and Ostriker 1978), the characteristic radius of a galaxy can be used as a measure of its dynamical evolutionary history, the galaxies with the largest characteristic radii having undergone the most mergers. The mean value obtained for the distant 3CR galaxies is significantly larger than that of the low redshift elliptical galaxies from the sample of Schombert (1987), which have \( r_e = 8.2 \pm 1.0 \) kpc, and is only about a factor of two smaller than the mean value for the low redshift brightest Abell cluster galaxies in the same sample \((r_e = 32.7 \pm 1.1 \) kpc; see Figure 3). Kormendy (1977) showed that the integrated luminosity \((\equiv \text{mass})\) of bright elliptical galaxies increases approximately as \( r_e^{0.7} \), and so the distant 3CR radio galaxies are only about a factor of two less massive than present day brightest cluster galaxies (BCGs). These galaxies must be very massive and highly dynamically evolved, even by a redshift of one.

Interestingly, at large radii a number of the 3CR galaxies show an excess of emission over that expected from the de Vaucouleurs profile. To increase the signal–to–noise of this feature, the galaxies with \( 1.0'' < r_e < 2.0'' \) were scaled by their characteristic radii and their profiles summed. Galaxies with smaller characteristic radii were not included because the effects of the seeing profile may still be important at a radius of about \( 3 r_e \), whilst larger galaxies were discarded because of low signal–to–noise in their outer regions. The combined profile is shown in Figure 4, and clearly shows an excess of emission beyond a radius corresponding to \( r \sim 35 \) kpc. This is the same radius as that beyond
Figure 2. Fits to the K–band radial intensity profiles of 12 3CR galaxies from the sample, using the sum of an unresolved point source (dash–dot line) and a de Vaucouleurs profile (dashed line). For each of the profiles, the effect of seeing has been taken into account. The sum of the two components is indicated by the solid line. In many cases the best fit does not involve a point source component, and so only the solid line is shown.
which halos are seen around cD galaxies in nearby clusters (e.g. Oemler 1976). Two observations dictate that this excess emission is not associated with the alignment effect: (i) well over 95% of the aligned emission of these galaxies lies within a radius of 35 kpc on the HST images; (ii) if the sample is split into galaxies with a strong and with a weak aligned component, the halo is seen with equal strength in each.

3 The cluster environments of the 3CR galaxies at redshift \( z \sim 1 \)

We have presented evidence that the distant 3CR galaxies are giant elliptical galaxies which: (i) have absolute K–magnitudes comparable to BCGs at redshifts \( z \gtrsim 0.7 \); (ii) have large characteristic radii, and are highly dynamically evolved; (iii) contain old stellar populations; (iv) show, in at least some cases, an excess of emission at large radii similar to the halos seen around cD galaxies.

Further evidence also suggests that powerful radio galaxies at high redshift \( (z \gtrsim 0.5) \) tend to lie in young or forming cluster environments (see Best et al. 1997b for a review). Specifically: (i) measures of the galaxy cross–correlation

**Figure 3.** Normalised cumulative frequency distributions of \( r_e \) for high redshift 3CR galaxies (solid line), low redshift brightest cluster galaxies (dotted line) and low redshift elliptical galaxies, excluding brightest cluster galaxies (dashed line). The latter two samples are taken from Schombert (1987).
The 3CR galaxies at $z \sim 1$

Figure 4. A combined K–band radial intensity profile for the 12 3CR galaxies with redshifts $0.6 < z < 1.8$ and characteristic radii $1.0 \leq r_e \leq 2.0$.

function (Yates et al. 1989) and an Abell clustering classification (Hill and Lilly 1991) both indicate that powerful FR II sources at intermediate redshift ($z \sim 0.5$) belong to environments of Abell class 0 richness or greater; (ii) powerful extended X–ray emission from the vicinity of a number of high redshift 3CR radio sources has been associated with cooling flows in relatively dense intracluster media (e.g. Crawford and Fabian 1996); (iii) [OII] 3727 emission line imaging has revealed companion galaxies near many of the radio sources (McCarthy 1988); (iv) multicolour imaging of the fields of powerful radio sources reveals a significant excess of galaxies with the red colours expected of a passively evolving population coeval with the radio source (e.g. Dickinson 1997); (v) the large Faraday depolarisation and rotation measures of these radio sources require a dense, ionised surrounding medium (e.g. Carilli et al. 1997); (vi) spectroscopic studies of the fields of some distant 3CR galaxies show them to lie in at least moderately rich clusters (Dickinson 1997).

In contrast, the amplitudes of the spatial cross–correlation functions for galaxies in the vicinity of nearby 3CR FR II radio sources are similar to those for normal elliptical galaxies (Prestage and Peacock 1988), whilst the host radio galaxies themselves have optical luminosities and characteristic sizes significantly less than those of first ranked Abell cluster galaxies (Lilly and Prestage 1987). Thus, powerful FR II radio galaxies at low redshift tend to lie in isolated environments or in small groups, whilst the distant 3CR radio galaxies
Best et al. (\(z > 1\)) appear to be associated with the brightest galaxies in rich cluster or proto–cluster environments. This dramatic change in the galactic environments of the 3CR radio galaxies, from richer to poorer environments with increasing cosmic time, indicates that the ‘uniform population’ interpretation of the K–z relationship, in which the host galaxies of distant 3CR radio galaxies evolve passively to become the equivalent of the hosts of nearby 3CR galaxies, cannot be correct.

4 The nature of powerful radio sources

To produce a powerful radio source, three essential ingredients are required: (i) a supermassive central black hole; (ii) a plentiful supply of gas to fuel the black hole; (iii) a dense surrounding medium to minimise adiabatic expansion of the radio lobes. The 3CR radio galaxies at \(z \sim 1\) release huge fluxes of kinetic energy in the form of relativistic jets, corresponding to the Eddington limiting luminosity of black holes with \(M \sim 10^8 - 10^9 M_\odot\) (Rawlings and Saunders 1991). Theoreticians have long argued that the masses of the central black holes should be roughly proportional to the masses of the host galaxies (e.g. Soltan 1982; Efstathiou and Rees 1988), and some evidence for such a correlation has recently been found for massive black holes in the nuclei of nearby galaxies (e.g. Kormendy and Richstone 1995). Massive central cluster galaxies would therefore be expected to host the most powerful central engines. In high redshift proto–cluster or young cluster environments, there will also be a plentiful supply of disturbed intracluster gas to fuel the central engine and confine the radio lobes. Furthermore, Ellingson et al. (1991) found that the velocity dispersions of galaxies around powerful distant radio sources are significantly lower (400 to 500 km s\(^{-1}\)) than those in comparably rich low redshift clusters (500 to 1000 km s\(^{-1}\)). These smaller relative velocities increase the efficiency of galaxy mergers, which may trigger the onset of the radio source (e.g. Heckman et al. 1986). Thus, massive galaxies in young cluster environments at high redshift possess all of the necessary ingredients for producing the most powerful radio sources.

Why then are the most powerful FR II radio sources at the present epoch not also associated with central cluster galaxies? The radio sources hosted by nearby BCGs are almost invariably ‘edge–darkened’ FR I type radio sources; their radio jets are of much lower kinetic power than the FR IIs and, according to current ideas, are strongly decelerated in the inner kiloparsec by entrainment of surrounding material (Laing 1993 and references therein), producing lower luminosity radio sources. Since neither the black hole mass nor the density
of the cluster environment can decrease with cosmic epoch, the availability of
fuelling gas must be the factor which limits the jet–powers of these sources.

Rich regular clusters at low redshift have had time to virialise the spatial
distribution of the galaxies, and for the intracluster gas to take up an equilib-
rium configuration within the cluster gravitational potential. The high velocity
dispersion of the galaxies in these clusters greatly reduces the merger efficiency.
Furthermore, studies of the Butcher–Oemler effect indicate that, compared to
high redshift clusters, there is a dearth of gas–rich galaxies close to the centre of
low redshift clusters which might merge with, and fuel, the central galaxy. The
evolution and virialisation of low redshift clusters is therefore likely to result in
a more restricted fuelling supply for the central engines of BCGs. Instead, the
most powerful FR II radio sources at small redshift are generally found in small
groups of galaxies: in these groups, velocity dispersions are small, mergers rela-
tively frequent, and gas–rich galaxies plentiful. Occasionally, dramatic mergers
will occur in low redshift BCGs, and we ascribe exceptional sources such as
Cygnus A (e.g. Fosbury, this volume) to this process.

These considerations suggest an explanation for the constancy of the stellar
masses of the 3CR galaxies throughout the redshift range $0.03 \leq z \leq 1.8$. This
mass may be interpreted as the typical mass which a giant elliptical galaxy
attains before its galactic and gaseous environment is virialised. Galaxies of
mass greater than a few times $10^{11} M_\odot$ will have undergone sufficient dynamical
evolution that they generally live in virialised environments where the reduced
supply of fuelling gas to the central regions results in FR I sources being formed.
This leads naturally to a correlation between the redshift of a 3CR FR II galaxy
and the richness of its environment: galaxies in highly overdense environments
accumulate matter the fastest, and therefore reach this ‘FR II upper mass limit’
at early cosmic epochs, whilst those which lie in less dense environments evolve
more slowly and can form powerful FR II radio galaxies at the current epoch.

5 Cosmic conspiracies in the $K–z$ relations

In light of these ideas, the $K–z$ relation of the 3CR galaxies can be compared
with those derived for other samples of galaxies, such as the 6C radio galaxies,
which are about a factor of five less powerful radio sources than the 3CR galaxies
at a given redshift (Eales and Rawlings 1996; Eales et al. 1997) and a sample of
BCGs (Aragón–Salamanca et al. 1993). In these cases, their mean $K–z$ relations
are broadly consistent with non–evolving stellar populations (see Figure [ ]). This
is remarkable, since undoubtedly their stellar populations must have evolved
significantly between redshift $z \sim 1$ and the present epoch. Indeed, the V–K colours of these galaxies are bluer at $z \gtrsim 0.5$ than they are nearby, consistent with passively evolving stellar populations (Aragón–Salamanca et al. 1993).

At high redshift ($z \sim 1$), the 6C radio galaxies have absolute K–magnitudes which are about 0.6 magnitudes fainter than those of the 3CR sample (Eales and Rawlings 1996; Eales et al. 1997; however, see also McCarthy, this volume) whilst at low redshift the two samples are equally luminous in the K–waveband. Eales et al. suggested that this effect might be associated with emission of the active galactic nucleus contributing directly or indirectly to the K–band flux density of the distant 3CR sources. The analysis of our HST and UKIRT observations presented in Section 2 demonstrates that these mechanisms can account for at most $\sim 0.3$ magnitudes of the difference. The greater K–band luminosities of the 3CR galaxies as compared with the 6C galaxies at high redshift must indicate, therefore, that they contain a greater mass of stars. It follows that, if there is a correlation between stellar mass and central black hole mass, the 6C galaxies possess less powerful central engines than the 3CR galaxies at high redshift, thus accounting for their lower radio luminosities. The overlap between the two samples on the K–$z$ relation would then arise from the scatter in the correlation between the stellar mass of the galaxy and the mass of the black hole (e.g. Kormendy and Richstone 1995).

At redshifts $z \lesssim 0.6$, the beam powers of all radio galaxies are well below the Eddington limit (Rawlings and Saunders 1991) indicating that their radio luminosities are determined predominantly by the availability of fuelling gas in the host galaxy and its environment, rather than by the black hole mass. A weaker correlation would therefore be expected between galaxy mass and radio luminosity at these redshifts, accounting for the similarity of the K–magnitudes for the low redshift 3CR and 6C galaxies.

Although the 3CR galaxies and BCGs are equally bright at redshifts $z \sim 1$, at low redshifts BCGs are up to a magnitude brighter in absolute K–magnitude than the 3CR galaxies. Since the stellar populations of the BCGs must have evolved over this redshift interval in a similar way to those of the 3CR galaxies, the shape of their K–$z$ relation must reflect the fact that BCGs continue to accumulate matter through mergers with massive cluster galaxies, and gas infall. Hierarchical clustering models for structure formation have suggested that the mass of BCGs increases by a factor of 3–4 between a redshift of one and the present epoch (Kauffmann 1995, Aragón–Salamanca et al. 1997).

For the BCGs, and also for the 6C galaxies, this growth of the mass of the galaxies between $z \sim 1$ and $z = 0$ increases their absolute magnitudes, thereby compensating for the dimming of their stellar populations — the two
effects conspire to give rise to apparently simple ‘no evolution’ tracks. The 3CR galaxies at high redshift also lie at the centre of galaxy clusters and so their masses would be expected to increase with cosmic epoch just like the BCGs; the ‘passively evolving’ K–z relation of these galaxies suggests, however, that this does not occur. This, too, is a conspiracy. The galaxies sampled at high and low redshifts do not form a uniform population, as is indicated by the dramatic change in their galactic environments with redshift. The apparent passive evolution disguises an important result: the most powerful FR II radio sources at all redshifts \( z \sim <1.5 \) contain approximately the same mass of stars, a few times \( 10^{11} M_\odot \).

6 Conclusions

We have presented evidence that powerful distant radio sources lie in (proto) cluster environments, and so provide a unique tracer of the most massive systems in the difficult redshift interval \( 1 \lesssim z \lesssim 3 \). Studies of the evolutionary state of such massive collapsed (or collapsing) structures at early epochs will provide important constraints upon theories of structure formation and galaxy evolution.

We have also demonstrated that the commonly–used ‘closed–box, uniform population’ galaxy evolution models are not appropriate for interpretations of the K–z relations. Instead, the shapes of these relations can be used to provide information about the merger histories of massive galaxies in clusters.

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