Faint radio samples: the key to understanding radio galaxies

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Abstract

The large number of differences between high- and low-redshift radio galaxies have almost all been discovered by looking at the bright 3C sample of radio sources. This has the disadvantage that the strong correlation between radio luminosity and redshift within a single sample makes it impossible to determine whether these differences are the result of cosmic evolution or whether they are simply the result of source properties depending on radio luminosity. The solution to this problem is to compare the properties of sources in faint samples with those of the 3C sources. I and collaborators have recently removed the degeneracy between redshift and radio luminosity by comparing the 3C sample to the recently completed 6C and 7C samples. In this paper I concentrate on what our study has revealed about the host galaxies of radio sources. At low redshift, radio galaxies are giant ellipticals with absolute magnitude being independent of radio luminosity over a range of $10^4$ in radio luminosity. At $z \sim 1$, the radio-luminous 3C radio galaxies are still giant ellipticals, but the 6C galaxies, only a factor of six lower in radio luminosity, are fainter by about 1 mag in the near-IR and have much more compact near-IR structures. At $z \sim 1$, radio galaxies follow a line in a diagram of optical luminosity verses de Vaucouleurs scale length parallel to the projection of the fundamental plane for nearby ellipticals in this diagram. I discuss the significance of these results for our understanding of radio galaxies and their evolution.
1 Introduction

There are sixty participants in this conference. As about half of my own circle of radio galaxy enthusiasts is here, I estimate that, in the whole world, there are about one hundred people interested in high-redshift radio galaxies. I suspect that in the nineteen eighties this number would have been higher, because, for a few years, radio galaxies were very fashionable, being then the only galaxies one could easily observe at high redshift and thus offering the only prospect of investigating the early evolution of galaxies. Well, fashion has moved on. The advent of faint galaxy redshift surveys, such as the Canada-France Redshift Survey, which have found large numbers of normal galaxies out to cosmologically-useful redshifts, the Hubble Deep Field, the successful implementation of the Lyman-break technique—all these have pushed radio galaxies off the catwalk. Radio galaxies are now recognised for what they really are: awkward objects that are neither entirely galaxy nor entirely quasar, objects whose properties at high redshift have a strictly limited applicability to the evolution of galaxies in general (except perhaps in the case of those objects with the lowest radio luminosities—Dunlop, this meeting). I actually find this new unfashionableness rather appealing. Since radio galaxies are interesting objects in their own right, it is quite pleasant not to have to strain to make tenuous connections to general issues of galaxy evolution. Paradoxically, however, it is just at the moment that radio galaxies seem deeply out of fashion that we are beginning to make significant progress in understanding radio galaxies as active galaxies, and I even have the suspicion that this may yet have relevance to broader aspects of galactic evolution.

Much of this recent progress has been made by studying faint samples of radio sources. As everyone at this conference knows, one of the biggest individual contributions to our field was made by Hyron Spinrad in his spectroscopic observations of the 3C sample in the seventies and eighties (the ”Spinrad era”, in George Miley’s words). Until recently the 3C sample was the only sample of radio sources with almost complete redshift information, and most of the very significant differences between high- and low-redshift radio galaxies (HZRG’s and LZRG’s, for short) were discovered from observations of the 3C sample. There are six differences I can think of: (1) HZRG’s have higher near-IR luminosities; (2) HZRG’s have bluer optical-near-IR colours; (3) LZRG’s and HZRG’s have radically different structures, the latter having typically a ‘bead of pearls ’ structure (HST observations have shown that this phrase does not do justice to the very bizarre structures of HZRG’s, which are impossible to sum up verbally, but
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which anyway look nothing like that of a giant elliptical; (4) The optical continuum structures of the HZRG’s, but not those of the LZRG’s, are aligned with their radio structures; (5) The emission-line luminosities of the HZRG’s are higher than those of the LZRG’s, and the line-emitting gas is frequently found in very extensive (D ∼ 100 kpc) nebulae; (6) The physical sizes of the radio sources associated with the HZRG’s are smaller, on average, than those associated with the LZRG’s.

Thus there are many differences between radio galaxies at high and low redshift, but our reliance on a single flux-limited sample (within which radio luminosity and redshift are tightly correlated—Fig. 1) has meant that it has been impossible to distinguish whether these differences are genuinely due to the effect of redshift (cosmic evolution) or are caused by the different radio luminosities of 3C radio galaxies at high and low redshift. As I will show, the way to determine whether we are seeing cosmic evolution or a luminosity effect is to obtain spectroscopic redshifts for faint samples, and for over ten years Steve Rawlings and I and a large number of collaborators (see acknowledgements) have been trying to obtain redshifts for faint samples selected from the Cambridge 6C and 7C radio surveys. One of the several advantages of these surveys is that they were carried out at 151 MHz, very close to the frequency of the 3C survey (178 MHz), thus reducing the well-known problem that the mix of radio morphologies in a radio sample, the distribution of radio spectral indices, and the proportions of the sources that are quasars and galaxies is a strong function of the selection frequency. There are several samples. The 6C ‘2-Jy’ sample has flux limits of approximately 2 and 4 Jy, the lower flux limit being about six times fainter than that of the 3C sample, and consists of 64 sources. Of these sources, only two (one of which is very close to a star) do not yet have redshifts. The 6C sample overlaps in area with the sample of Allington-Smith which was selected from the 408-MHz B2 survey. The combined 6C/B2 sample contains 80 sources. All the infrared imaging data for these samples has now been published and forthcoming papers will present the redshifts and technical details about the samples. There are various 7C samples (Lacy, this meeting), which are all about four times fainter than the 6C sample. These samples have been mainly studied by the Oxford group, and there are now redshifts for ≃ 90% of the sources. The 7C samples are even a shorter distance along the road to publication than the 6C sample. These faint samples are the only ones of which I am aware which have such complete redshift information.

Figure 1 shows the 3C and 6C samples plotted on the radio luminosity-redshift plane. As for 3C, within the 6C sample there is a tight correlation between redshift and radio luminosity. However, the combination of samples
Figure 1. Radio luminosity at 151 MHz in W Hz$^{-1}$ sr$^{-1}$ versus (1 + z) for the 3C sample (open circles) and the 6C sample (filled circles). A Hubble constant of 50 km s$^{-1}$ Mpc$^{-1}$ and a density constant of 1 have been assumed.

allows one to disentangle the effects of redshift and radio luminosity. At any redshift, the combination of the samples provides a sufficient range of radio luminosity for one to look for correlations between a third property and radio luminosity. Similarly, there is a large range of redshift at any radio luminosity for one to look for the effects of cosmic evolution without the worry that any effect could be caused by the radio luminosities of the high-redshift sources being different from those at low redshift. The 7C sources fall below the 3C and 6C sources in this diagram, extending the range of radio luminosity at constant redshift and the range of redshift at constant radio luminosity.

2 What we have learned from the faint samples

Our study of the faint low-frequency samples has allowed us to answer three basic questions about radio galaxies.

2.1 Why is it hard to measure redshifts for faint radio sources?

Studies of the 3C sample$^{7,8}$ have shown that emission-line luminosity and radio luminosity are strongly correlated, but without considering fainter samples it is impossible to determine whether this is the true correlation or whether the true
correlation is between emission-line luminosity and redshift. Although a full quantitative analysis of our 6C spectra is still in progress, it is already obvious that 6C galaxies have weaker lines than 3C galaxies at a similar redshift. This shows that the true correlation is between emission-line luminosity and radio luminosity. One plausible (although not unique) explanation of this correlation is that both the emission-line luminosity and the radio luminosity are measuring the ‘power of the central engine’, the emission-line luminosity because it is from gas which is being photoionized by radiation from the active nucleus and the radio luminosity because it is a strong function of the kinetic power of the beam being produced by the active nucleus. From the point-of-view of an observer, the message of the correlation between radio and emission-line luminosity is that there is a limit to how faint one can go in radio flux and still obtain complete redshift information. The 7C sample is about twenty times fainter than 3C, and we believe that this is as faint as is practical to go with 4-m telescopes. Any fainter, as Jim Dunlop will show in his talk, and you are in the regime of the 8- and 10-m telescopes.

2.2 Do the sizes of radio sources change with redshift?

One of the earliest discoveries about high-redshift radio sources was the discovery that the radio sizes of high-redshift quasars are smaller than those of quasars at low redshift\textsuperscript{10,11} (I would be interested to know if there are any earlier references on this subject than 1970). Of course, because of the correlation between radio luminosity and redshift within a bright sample, it is possible that this discovery actually means that radio sources with high radio luminosities have smaller radio sizes than those with low radio luminosities. Since those early days there has been a veritable industry trying to disentangle the correlations and to determine the strength of the evolution (if it is evolution). In principle, by comparing the sizes of sources from the 6C and 7C samples with the sizes of sources of similar luminosities in the 3C sample, it should be possible to get an unambiguous measurement of the strength of any evolution, and by comparing 6C/7C sources with 3C sources at a similar redshift it should be possible to look for correlations of size with radio luminosity. One of the biggest problems in this kind of analysis is that the sizes of sources depend on the selection frequency of the sample in which they were found, because high-frequency samples tend to contain more compact sources (both steep spectrum and flat spectrum). The closeness of the selection frequencies of 3C, 6C and 7C means that, for avoiding this problem, this combination of samples is almost but not quite ideal. That the combination is not quite ideal is because of a fairly subtle point. Suppose
one has selected a sample at a particular frequency, the frequency at which the radiation was emitted by one of the sources in the sample will have been higher than the selection frequency by a factor \((1 + z)\). If one is comparing sources of a similar radio luminosity in a bright and a faint sample, the \(1 + z\) factor will be larger for the faint sample than the bright sample, meaning that the effective selection frequency of the faint sample will be higher than that of the bright sample even if the actual selection frequencies were the same, raising the possibility again that spurious cosmological evolution could be seen because of the proportion of compact sources increasing with selection frequency. Thus it would be preferable if the selection frequency of the 6C/7C samples was even lower than 151 MHz. Nevertheless, for a comparison with 3C, the low selection frequency and the large percentage of redshifts means that these faint samples are the best available.

A couple of years ago, Mark Neeser and I did a linear-size analysis\(^{15}\) using the 6C and 3C data and found rather weaker cosmological evolution \((D_{\text{med}} \propto (1 + z)^{-1.5})\) than had previously been claimed and no evidence for a correlation between radio size and radio luminosity. This evolution can be seen visually in the P-D diagrams of the two samples (Fig. 2) by looking at the ‘clump’ of sources in the 6C diagram with sizes of about 100 kpc and luminosities between \(10^{27}\) and \(10^{28}\) W Hz\(^{-1}\) sr\(^{-1}\). Most of the sources in this clump actually have sizes less than 100 kpc, whereas in the same luminosity range in the 3C diagram there is much larger fraction of sources with sizes greater than this. We found the apparent clump quite intriguing because, as in the case of the H-R diagram, the distribution of objects in the P-D diagram should reflect the relative times that sources spend at different stages of their evolution\(^{16,17}\). Furthermore the physical sizes of the clump sources are very similar to the typical sizes of the gaseous nebulae found around HZRG’s, and we constructed a simple model in which the evolution of a high-redshift source is strongly affected by the presence of one of these nebulae.

At this time we thought we had had the last word on the subject, both because of the quality of our data and because we had spotted a hitherto unrecognised selection effect which we thought had caused other groups to detect too strong evolution. It was therefore quite stimulating to hear Pat McCarthy at this meeting say that, on the basis of the MRC 1-Jy sample, he and his collaborators see much stronger linear-size evolution than we found, a correlation between radio size and radio luminosity, and no clump. How do we resolve this disagreement? I am suspicious that the differences are caused by the selection-frequency effect. As discussed above, the effective difference between the selection frequencies of the MRC and 3C samples is greater than the difference
Figure 2. Radio luminosity at 151 MHz in W Hz\(^{-1}\) sr\(^{-1}\) versus source size in kpc for the 3C sample (a) and for the 6C sample (b). On both graphs the filled circles represent FR2 sources and the open circles sources with other morphologies. The horizontal lines indicate the approximate luminosities that sources with redshifts of 0.5, 1, and 2 would have in the two samples.

between the actual frequencies (408 MHz and 178 MHz), and this could produce a larger fraction of compact sources in the MRC sample than we find in the 6C sample. Fortunately, the quality of the data for all faint samples is now such that we can go beyond mutual suspicion. By comparing the P-D diagrams of the 6C, 7C and MRC samples, and in particular by plotting the P-D diagrams for the various morphological classes within these samples, we should be able to determine immediately why we obtain different results. Overall, I think there is the prospect of a rapid advance in this area, since for the first time we can plot P-D diagrams for samples of different flux densities and selection frequencies which are not missing high-redshift sources and sources of large angular size—
two problems that bedeviled early investigations in this area. Our theoretical understanding of the P-D diagram is also advancing at a satisfactory result. We are beginning to understand the evolutionary connections between different morphological classes, and there are finally theoretical models that predict, in a natural way, some of the gross features of the P-D diagram.

2.3 What kind of galaxies are high-redshift radio galaxies?

One of the few unassailable facts in our field is that at low redshift radio galaxies are giant ellipticals with a small spread of absolute magnitude. It is worth reminding ourselves that, beyond some hand-waving theorizing, we still do not understand why this should be. When one thinks about it, it is quite surprising that, over a range of $10^4$ in radio luminosity, there is no clear relation between radio and optical luminosity. Although optical images of HZRG's look nothing like giant ellipticals, until recently it had been possible to hope that HZRG's are still essentially giant ellipticals, with the optical emission being due to 'fireworks' occurring in the rest-frame ultraviolet, either nonstellar emission from the active nucleus or emission from star-formation regions (producing a lot of light but of relatively low mass compared to the mass of the galaxy as a whole). The true test of this idea is to make observations in the near-infrared, since these will be sensitive to the old stellar population and will be relatively unaffected by nonstellar light or light from young high-mass stars. These observations have recently shown that this basic fact may be true at $z = 0$, but it is not true at $z \sim 1$.

A couple of years ago, when we started measuring K-magnitudes for 6C galaxies we were surprised to discover that at $z \sim 1$ 6C galaxies are systematically fainter by about 0.6 mags than 3C galaxies at similar redshifts. This is quite a remarkable result, and very different from the situation at low redshift, since it shows there is a correlation between radio and near-IR luminosity over a range of only $\sim 6$ in radio luminosity. Our first thought was that we were seeing the effect of nonstellar emission. There is plenty of evidence from polarization studies of scattered nonstellar light from HZRG's in the optical waveband; if nonstellar light is also making a significant contribution in the K-band (either scattered light or emission directly from the active nucleus), then one would expect 3C galaxies to be brighter in the near-IR than 6C galaxies, because of their greater radio luminosities and thus presumably more powerful active nuclei. There is some evidence for nonstellar K-band emission from high-redshift 3C galaxies. In the K-band the narrow-line radio galaxy 3C 22 has the properties of a quasar: a bright unresolved continuum source and broad lines. There
is evidence in a few cases that the K-band light is polarized\textsuperscript{24}, suggesting a scattered component to the K-band light. But the K-band morphology of 3C 22 is almost unique—virtually all 3C galaxies are extended in the K-band—and the fraction of the K-band light that is estimated, from the polarization measurements, to be scattered is insufficient to explain the large difference between the near-IR luminosities of the 3C and 6C galaxies. The most conclusive arguments against this hypothesis, however, come from recent high-resolution K-band imaging of 3C and 6C galaxies.

Best and collaborators\textsuperscript{25,26} have recently shown that the K-band structures of high-redshift 3C radio galaxies are well-fit by the de Vaucouleurs profiles typical of giant ellipticals. Using the REDeye camera on the CFHT, we have carried out a similar imaging survey of 6C galaxies at $z \sim 1$\textsuperscript{27}. We too find that the intensity profiles can be adequately fitted by a de Vaucouleurs profile, but with the 6C galaxies having, on average, a much smaller value of the de Vaucouleurs radius than the 3C galaxies. Both sets of data are plotted in Fig. 3, which shows that 6C galaxies at $z \sim 1$ are both less luminous in the K-band than 3C galaxies at a similar redshift and also have more compact structures. The difference in luminosities is actually $\approx 1$ mag, which is greater than the difference we found before\textsuperscript{13}; the discrepancy arising because in the former study we compared aperture magnitudes, whereas the magnitudes plotted in the figure are total magnitudes (see \textsuperscript{27} for a discussion). The 3C and 6C HZRG’s follow a line in the diagram which lies roughly parallel to the line followed by low-redshift ellipticals.

The study of Best et al. is conclusive evidence that in general the K-band light from 3C galaxies at $z \sim 1$ is not dominated by nonstellar emission. Although our study of 6C galaxies had similar angular resolution ($\approx 1$ arcsec) to the 3C study, the much more compact structures of the 6C galaxies mean that our limits on the presence of nuclear nonstellar sources are less stringent than the limits for the 3C galaxies. However, if there were nuclear nonstellar sources in the 6C galaxies but not in the 3C galaxies, this would mean that the difference between the luminosities of the host galaxies would be even greater than is apparent in Fig. 3. Moreover, it would be most surprising if the less radio-luminous galaxies (and thus presumably the ones with the less powerful active nuclei) had stronger nuclear nonstellar K-band sources; as well as being the opposite of the explanation that we originally proposed for the difference in the K-band luminosities. The compact structures of the 6C galaxies mean that we can also not prove that these galaxies are elliptical galaxies: the measured intensity profiles are consistent with both de Vaucouleurs and exponential profiles. However, as in the case of the nuclear nonstellar sources, it seems sensible
Figure 3. Estimated half-light radius, which is here equal to the de Vaucouleurs radius, versus optical luminosity for high-redshift 6C galaxies (filled circles) and high-redshift 3C galaxies (open circles). The dashed line shows the track in the diagram followed by nearby ellipticals. See [27] for a full discussion of how this diagram was constructed.

to make the least radical assumption. Therefore, we will assume, until shown otherwise, that the K-band emission from a 6C galaxy at $z \sim 1$ follows a de Vaucouleurs profile, and that there is negligible contribution from a nuclear source.

Figure 3 immediately raises four questions: (1) What is the cause of the correlation between radio luminosity and near-IR luminosity seen at $z \sim 1$? (2) Why is such a correlation not seen at low redshift? (3) What will the 6C galaxies at $z \sim 1$ evolve into at $z = 0$? (4) What will the 3C galaxies at $z \sim 1$ evolve into at $z = 0$? I will try and answer the last two questions first, because I and my collaborators and Philip Best and his collaborators have independently reached the same conclusion. While not guaranteeing the solution is correct, it at least ensures that nobody will disagree with me at this meeting.

The dashed line in Figure 3 is a projection of the fundamental plane for nearby elliptical galaxies. As one would expect, low-redshift FR2 radio galaxies, being ellipticals, lie approximately along this line, most of them having lower values of the de Vaucouleurs radius than the 3C HZRG’s. The 6C and 3C HZRG’s must evolve in such a way as to reach this line by the current epoch. There are two evolutionary mechanisms which will cause galaxies to move across the diagram. Simple stellar evolution will cause a galaxy to move horizontally
across the diagram. If, as has been suggested, most of the stars in a radio
galaxy form at a very early time, the expected amount of passive stellar evolution
between $z = 1$ and $z = 0$ is just about enough to move the HZRG’s onto the zero-
redshift line$^{27}$. The other type of evolution that can occur is merging. The effect
of homologous merging is to make galaxies more diffuse and more luminous$^{28}$,
moving them to the top left in Fig. 1. This allows us to make a strong inference.
Even if there is no merging, 3C galaxies at $z \sim 1$ can not evolve into low-
redshift FR2’s. Their structures are already too extended (they have too large
de Vaucouleurs radii) at $z \sim 1$ compared with low-redshift FR2’s. If there
is any merging, making the 3C galaxies even more extended, this conclusion
is only strengthened. So what do 3C HZRG’s evolve into? A plausible step
beyond this initial conservative conclusion is to assert that 3C HZRG’s evolve
into first-ranked cluster galaxies at the current epoch. There are two pieces
of evidence for this. First, although there has been no systematic statistical
investigation of the environments of 3C galaxies at $z \sim 1$, there is evidence in
many individual cases of surrounding clusters or of dense surrounding gas$^{25}$. If
a radio galaxy is in a cluster at $z \sim 1$, it will still be in a cluster at the current
epoch. Second, the de Vaucouleurs radii of 3C HZRG’s are lower but not much
lower than first-ranked cluster galaxies, which means that it would not require
much merging between $z \sim 1$ and $z = 0$ to give a 3C galaxy the intensity profile
of a first-ranked cluster galaxy. As the timescale for the evolution of a radio
source is only $10^8$ years$^{18}$, there is no reason why a 3C HZRG need be a radio
source at all at the current epoch and, as I have argued, it can not turn into
an FR2. It is possible, however, that the ultimate descendant of a 3C HZRG
could be an FR1, since these radio sources tend to be found in clusters and are
frequently associated with first-ranked cluster galaxies$^{29}$.

One can make a less definite answer to the question about the descendants
of 6C HZRG’s. Since these have much lower de Vaucouleurs radii than the 3C
HZRG’s, they would have to undergo much more merging to turn into first-
ranked cluster galaxies at the current epoch. Because of the very similar de
Vaucouleurs radii, it seems most plausible that 6C HZRG’s simply turn into
ellipticals like those that host FR2’s at the current epoch. If this is true, then
as low-redshift FR2’s tend to be found in quite isolated environments$^{29}$, this
suggests a way of testing the answers to both questions (3) and (4). If these
answers are correct, 6C HZRG’s should be in environments of much lower density
than 3C HZRG’s. Testing this is quite difficult. At present the best way of
doing this seems to be to extend the galaxy-counting techniques that have been
applied to the environments of radio galaxies at slightly lower redshifts$^{30,31}$, but
in the near-IR rather than in the optical, since the contrast of any high-redshift
cluster against the unrelated field galaxies is higher at longer wavelengths. We are currently trying to do this in collaboration with Hans Hippelein using the OMEGA camera at the Calar Alto Observatory. In the medium term, the best prospect of testing these answers is AXAAF.

If we now return to the first two questions, there seem to me two ways one can try and answer these. Philip Best and his collaborators\textsuperscript{25,26} suggest that the correlation between radio and near-IR luminosity at $z \sim 1$ is due to the mass of the central black hole being proportional to the mass of the galaxy. The bulk kinetic power of radio jets in 3C galaxies at $z \sim 1$ is close to the Eddington limiting luminosity of a black hole of mass $\sim 10^8 \, M_\odot$, and Best et al. argue that this suggests the bulk kinetic power is primarily determined by the black hole mass rather than the fueling rate of the black hole—which is quite plausible given the evidence for substantial amounts of gas around HZRG’s. In this model, the lack of a correlation between radio and near-IR luminosity at lower redshifts is due to the less plentiful supply of fuel, which means that fuel supply, rather than black hole mass, becomes the main determinant of jet power.

Radio luminosity is not just dependent on the bulk kinetic power of the radio jet, it is also dependent on the density of the surrounding gas\textsuperscript{32}, and I believe it is equally plausible to argue that at $z \sim 1$ radio luminosity depends on stellar luminosity simply because galaxies that are massive are surrounded by denser, more extended distributions of gas. I do not have a convincing explanation of why this correlation should disappear at low redshift, beyond the speculation that since the gas around HZRG’s is of a very different character to that around LZRG’s (a much larger mass of line-emitting gas at $10^4 \, K$), it is possible that there is a relation between gas mass and stellar mass at high redshift which disappears at low redshift. Finally, I must mention one intriguing point noticed by Nathan Roche. Although for LZRG’s optical luminosity is independent of radio luminosity over a range of $10^8$ of radio luminosity, the line dividing FR2’s and FR1’s is not independent of optical luminosity\textsuperscript{20}. Since this line has roughly the same relation as that seen between near-IR and radio luminosity at high redshift, might this be the fossil of the high-redshift effect?

3 Unanswered Questions

I do not regard any of the questions posed in the last section as being conclusively answered. I believe the importance of Figure 3 is that it has suggested questions one stands a chance of answering, questions which are particularly important because of their connection to such long-standing fundamental questions about
radio galaxies as, why are low-redshift FR1’s found in denser environments than FR2’s? What do radio galaxies evolve into? Why are low-redshift radio galaxies always giant ellipticals? The 6C and 7C samples provide a basis for obvious observational projects that should go a long way to answering these questions. First, one would like to put Fig. 3 on a firmer footing. It has been produced from ground-based imaging, and in the case of the 6C galaxies, although we are sure that the K-band emission is compact, we cannot put stringent limits on the presence of point sources or even be sure that the 6C galaxies are ellipticals rather than disk galaxies. With NICMOS it will be possible to determine how near-IR structure depends on radio luminosity with much greater certainty. Second, one would like to know how the relation between near-IR structure/luminosity and radio luminosity continues to lower radio luminosities. It will be possible to investigate this by making high-resolution near-IR observations of the 7C galaxies. Third, one would like to know how other indicators of the power of the central engine depend on radio luminosity. Two properties which may (but not definitely) depend on central-engine power are the luminosity of the emission lines and the strength of the aligned optical component, and observations of 3C, 6C and 7C galaxies at similar redshifts will show how both of these depend on radio luminosity (Mark Lacy and collaborators have already made a start on the second of these—this meeting). Fourth, one would like to know how, at high redshift, radio luminosity depends on the density of the environment. The answer here lies in counting galaxies on near-IR images of 3C, 6C, and 7C galaxies, and, in the longer term, in AXAAF observations.

Finally, although I have argued that one does not need to justify one’s interest in HZRG’s by making a connection to the evolution of the general galaxy population, I cannot resist one speculation. Figure 3 shows that, at $z \sim 1$, although the rare radio-luminous 3C galaxies are in large elliptical galaxies, most radio galaxies are in more compact galaxies. Might this not be connected to the apparent absence of large elliptical galaxies in the Hubble Deep Field?  

### 3.1 Acknowledgements and References

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