The evolution of the cluster environments of radio sources at $z < 1.8$

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**Abstract.** An analysis of the cluster environments around distant radio galaxies is presented, in particular the results from new NTT deep optical–IR imaging of the fields of radio sources at $z \sim 1.6$. A net overdensity of K-band galaxies is found, together with a sharp peak in the angular cross-correlation amplitude, centred on the radio galaxies. This excess clustering is associated predominantly with red galaxies, with colours consistent with being old ellipticals at the radio source redshift. A large excess of such red galaxies is seen, particularly within 100 kpc of the radio source. These comprise amongst the most distant red sequences of cluster ellipticals yet discovered, that is, the highest redshift ‘normal’ clusters.

1. **Introduction**

The discovery and study of clusters at redshifts beyond one is of great importance for many aspects of structure formation and cosmology, as discussed throughout this volume. Unfortunately, identification of clusters at these redshifts is very challenging observationally: at X-ray wavelengths existing surveys suffer sensitivity limits and the field of view of the current generation of X-ray telescopes make them inefficient for wide-area surveys; at optical and near-infrared wavelengths distant clusters show only low contrast above the high background counts at faint magnitudes. Fortunately an alternative method of locating distant clusters does exist, using powerful radio sources as probes.

Radio sources are hosted by giant elliptical galaxies (e.g. McLure & Dunlop 2000, Best et al 1998) and are amongst the most massive galaxies known in the early Universe. At low redshifts they are typically found in galaxy groups, or poor clusters, but environmental richness appears to increase with redshift: at $z \sim 0.5$, the large amplitude of the galaxy cross-correlation function around radio galaxies and an Abell clustering classification indicate that about 40% of radio sources are located in clusters of Abell richness class 0 or greater (e.g. Hill & Lilly 1991). At $z \sim 1$ there is overwhelming evidence from observations
at a wide variety of wavelengths that at least some powerful radio sources are located at the centres of clusters (e.g. Best 2000 and references therein). Best (2000) analysed UKIRT K–band data of a sample of 3CR radio galaxies at $z \sim 1$ and found a sharp peak in the cross–correlation function surrounding the radio galaxies, corresponding to a mean environmental richness of between Abell class 0 and 1. Colour–magnitude (C-M) relations showed red sequences around some (but not all) radio sources (see also Barr et al, this volume), but a detailed analysis of the C-M relations and the source–to–source variations was prohibited by the small field of view (70 by 70 arcsec) of the UKIRT frames.

At still higher redshifts, strong evidence is found for (proto-)clusters around radio galaxies at $z > 2$ (e.g. Pentericci et al, Kurk et al, this volume). At these redshifts, however, studies have been limited to objects selected by line emission: the sequence of red galaxies characteristic of low redshift clusters is not seen.

In this article the first results are presented of a very deep optical–IR imaging study of the environments of radio sources at $1.44 < z < 1.7$, in order to investigate their environments, to determine to what redshift the centres of clusters are dominated by a population of red galaxies, and ultimately to use this red sequence to investigate the evolution of the cluster ellipticals.

2. The fields of radio galaxies at $z \sim 1.6$

We have defined a complete subsample of 9 radio sources with redshifts $1.44 < z < 1.7$ and galactic latitudes $|b| > 20^\circ$ from the equatorial sample of Best et al (1999; $S_{408\text{MHz}} > 5\text{Jy}$; $-30 < \delta < +10^\circ$). Deep 5 by 5 arcminute R, J, K images of the fields of five of these sources were obtained in Sept 2000 and Aug 2001 using the NTT, reaching typical depths of $K \sim 20.5$, $J \sim 22.3$ and $R \sim 26$. Although final results await the completion of the imaging program, these multi–colour data provide some promising early results, including:

- An excess of K–band counts. The number counts in the infrared K–band have been determined as a function of magnitude in each field (see Table 1). These results show a clear excess of number counts fainter than $K \sim 18.5$. Note that the magnitude of the radio source host galaxy is typically $K \sim 18$.

- A peak in the angular cross–correlation function around the radio sources. For each field the angular cross–correlation function has been determined following the method outlined by Best (2000); cross–correlation statistics have been calculated both for all galaxy–galaxy pairs, and for only radio galaxy–galaxy pairs. Combining the data from the different fields, there is a clear excess of clustering around the radio host galaxies, as compared to the field in general (Figure 1), the mean cross–correlation amplitude indicating cluster environments of Abell richness class 0 to 1. To investigate how the cross–correlation amplitude varies with galaxy colour, the data were split into different colour bins. The clustering excess is predominantly associated with red galaxies; those galaxies with colours consistent with being cluster ellipticals are very strongly clustered around the radio galaxy, whilst blue galaxies show no excess clustering. There is some field-to-field variation; this will be investigated when the dataset is completed.

- Overdensities of red galaxies. In many of the fields there is a large overdensity of extremely red galaxies (see also Hall et al 2001), with colours consistent with passively evolving elliptical galaxies at the radio source redshift. There is
| $K$ | Raw Counts | Corrected Counts | Counts per mag. | Error* | Literature Counts* | Excess Galaxies |
|-----|------------|------------------|-----------------|--------|--------------------|-----------------|
| 15.0–15.5 | 3 | 3.0 | 308 | 177 | 218 | 0 |
| 15.5–16.0 | 5 | 5.0 | 513 | 229 | 620 | 0 |
| 16.0–16.5 | 7 | 7.0 | 719 | 271 | 960 | −1 |
| 16.5–17.0 | 23 | 23.0 | 2362 | 492 | 1530 | 3 |
| 17.0–17.5 | 32 | 32.3 | 3320 | 587 | 2530 | 3 |
| 17.5–18.0 | 52 | 52.5 | 5396 | 751 | 5540 | 0 |
| 18.0–18.5 | 95 | 96.9 | 9958 | 1041 | 9470 | 2 |
| 18.5–19.0 | 128 | 130.6 | 13418 | 1295 | 10500 | 9 |
| 19.0–19.5 | 208 | 214.4 | 22029 | 1613 | 11600 | 34 |
| 19.5–20.0 | 276 | 293.6 | 30164 | 2068 | 17200 | 42 |
| 20.0–20.5 | 294 | 381.8 | 39226 | 3565 | 22700 | 54 |

Table 1. The K–band number counts combined across the radio galaxy fields. (*: counts per magnitude per square degree.)

Figure 1. Angular cross–correlation analyses of the fields of the 3 radio galaxies observed in Sept 2000. The left–hand plots consider all galaxy–galaxy pairs, and the right–hand plots only radio galaxy–galaxy pairs. The upper plots are for all of the galaxies in the field, and show a clear excess of clustering around the radio galaxy. The middle plots show blue galaxies, demonstrating that these have no preferential clustering around the radio galaxy. The bottom plots are for galaxies with colours consistent with being old elliptical galaxies at the radio source redshift: these have a remarkably high cross–correlation amplitude.
Figure 2. $R - K$ colour histograms for galaxies around 2025-155, as a function of distance from the radio source: Upper left – 0 to 100 kpc radius; Upper right – 100 to 250 kpc radius; Lower left – 250 to 500 kpc radius; Lower right – 500 to 1000 kpc radius. Note the strong excess of galaxies with very red colours, particularly in the inner 100 kpc.

especially strong clumping of red galaxies on a $\sim 100$ kpc scale. This can be seen, for example, in colour cuts as a function of radius (Figure 2).

3. Conclusions

We have presented some of the first results of a program of optical–IR imaging of the fields of radio galaxies at redshifts $z \sim 1.6$. Three different analyses all provide strong evidence for significant galaxy overdensities around some of these radio sources. Work to spectroscopically confirm these redshift and to study the properties of the cluster galaxies is continuing. The presence of the extremely red galaxies is particularly exciting, as it indicates that a substantial population of elliptical galaxies have already formed, and must have ceased star formation a significant time ($\gtrsim 1$ Gyr) before redshift 1.5. This red sequence also makes these amongst the most distant ‘normal’ clusters known, and thus offers unique prospects for advancing studies of galaxy formation and evolution.

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