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Searches for High Redshift Radio Galaxies

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Searches for High Redshift Radio Galaxies

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Abstract

We have started a search for High Redshift Radio Galaxies (HzRGs) in an area covering 7 sr by selecting a sample of Ultra Steep Spectrum (USS) sources with a low flux density cut-off $S_{1400} > 10$ mJy and a steep spectral index $\alpha < -1.3$ ($S \propto \nu^{\alpha}$) using the WENSS, NVSS and TEXAS radio surveys. Preliminary results for 25 sources shows that we are almost twice as effective in finding HzRGs than previous searches using brighter radio sources and less steep radio spectra ($\alpha < -1.0$). The redshift distribution is consistent with an extension of the $z - \alpha$ relation to $\alpha < -1.3$, but a large fraction of our sample (40%) consists of objects which are too faint to observe with 3–4m class telescopes. The first results from our Keck K-band imaging and spectroscopy program indicate that these faint objects are our best candidates to detect HzRGs at $z > 3.5$. Our search is aimed at significantly increasing the number of very high redshift radio galaxies for further detailed studies of the formation and evolution of massive galaxies and their environment.

1 Introduction

Detailed spectroscopic and morphological studies of High Redshift Radio Galaxies (HzRGs) are important for the understanding of the formation and evolution of massive elliptical galaxies. Unlike quasars, the light from HzRGs is not dominated by the (non-stellar) AGN component but is spatially resolved, allowing us to get a clearer view of the host galaxy and its young stellar population. Two dramatic examples of this are the recent discovery of jet-induced star formation in the HzRG 4C 41 17 at $z = 3\ 8$ (Dey *et al* 1997), and the strong morphological evolution of HzRGs between $2 < z < 4\ 4$ (van Breugel *et al* 1998)

Unfortunately, the number of known HzRGs rapidly decreases at high redshift (Fig 1) At present, 125 radio galaxies with $z > 2$ are known, of which 20 have $z > 3$ and only 3 have $z > 4$ Complete, flux-limited radio surveys, like the 3CR (Spinrad *et al* 1985) and MRC/1Jy (McCarthy *et al* 1996) surveys have failed to yield significant numbers of HzRGs (see Table 1) The most efficient way of finding HzRGs is to concentrate on radio-sources with an ultra-steep radio spectrum Half of the $z > 2$ radio galaxies know today have been discovered from several samples of USS ($\alpha \lesssim -1$) radio sources (Blundell *et al* 1998, Röttgering *et al* 1997, Chambers *et al* 1996) Figure 1 shows the contribution of USS selected sources (shaded) to the total number of known $z > 2$ HzRGs All the $z > 3\ 5$ radio galaxies were found from targeted USS samples

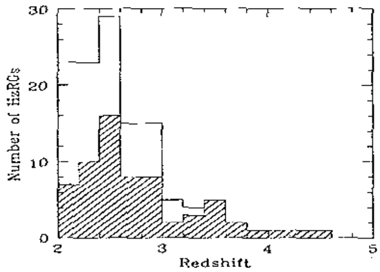

Figure 1 Known $z > 2$ Radio Galaxies The contribution of sources found from ultra steep spectrum samples is shaded

2 A sample of USS sources from new radio surveys

With the advent of the 325 MHz WENSS (Rengelink *et al* 1997), the 365 MHz TEXAS (Douglas *et al* 1996), the 1 4 GHz NVSS (Condon *et al* 1998) and the 1 4 GHz FIRST (Becker *et al* 1995) surveys it is now possible for the first time to define a large sample of USS sources with even steeper spectral indices ($\alpha \lesssim -1\ 3$) covering the entire sky North of declination $-35°$, and using 10 – 100 times lower flux density limits than has been possible before (Röttgering *et al* 1994) We briefly describe our 2 subsamples below More details will be given in De Breuck *et al* (1998)

2.1 The WENSS/NVSS (WN) sample

A correlation of 1998 January versions of the WENSS and NVSS catalogues provided spectral indices for 143,000 sources, of which we selected the 0.9% with spectral indices $\alpha_{1400}^{325} < -1.3$. Several additional selection criteria were applied to the sample. (i) $S_{1400} > 10$ mJy, to obtain spectral indices accurate to $\lesssim 0.1$, (ii) Galactic latitude $|b| > 15°$, to avoid excessive Galactic extinction, and (iii) only single-component sources in the WENSS and NVSS surveys (54″ and 45″ resolution) were retained. Unlike some other USS samples (*e.g.* the 6C*, Blundell *et al.* 1998), we did not apply additional size cut-offs, as HzRGs exist with angular sizes up to 54″ (4C 23.56 at $z = 2.479$, Chambers *et al.* 1996, our WN sample also contains a $z = 3.215$ galaxy of 26″). The present WN sample consists of 354 USS sources.

2.2 The TEXAS/NVSS (TN) sample

The WENSS survey covers the sky north of $\delta = +29°$. In order to obtain a more Southernly sample of USS sources in the area outside WENSS ($-35° < \delta < +29°$), we correlated the TEXAS 365 MHz survey with the NVSS. In addition to the same selection criteria used for the WN sample, we have also excluded 50% of the sources with questionable fluxes or positions in the TEXAS catalogue Douglas *et al.* 1996.

2.3 High-Resolution Radio Images from FIRST and VLA observations

The WENSS, Texas and NVSS surveys, from which the described USS samples have been defined, do not provide high enough positional accuracy or resolution for the optical identification of the radio sources, which we preselected to be undetected on the POSS plates ($m_R > 20$).

We therefore correlated our WN sample with the FIRST catalogue (Becker *et al.* 1995) which has accurate positions ($\lesssim 0\farcs5$), and nine times better resolution (5″). Unfortunately, the present coverage of the FIRST survey overlaps with only 40% of our WN/TN samples. We therefore observed 239 sources in our sample outside the FIRST area with the VLA in A and BnA arrays. The observations were made at 4.8 GHz to obtain $0\farcs5$ to 1″ resolution and to determine spectral curvature.

2.4 Optical Spectroscopy and Near-IR imaging

Spectroscopic observations of our sample with the Lick, ESO 3 6m and WHT telescopes has yielded firm redshifts for 14 sources from the WN and TN samples The median redshift is $z = 2\ 4$, only 4 have $z < 2$, while 5 have $2 < z < 3$, 4 have $3 < z < 4$, and 1 has $z = 4\ 13$ For ~40% of the sources observed, we could not yet determine the redshift because either no object or no emission lines were detected

We have started a project to obtain K-band images of these faint objects using the Near-IR Camera (NIRC) on Keck I Our first results on 8 galaxies have yielded K-band magnitudes in the range 18 4 – 22 7 (4″ aperture) On the basis of the Hubble $K - z$ diagram (Fig 2), we predict that 2 objects will be at $z \sim 1$, 4 will be at $3 < z < 4$, and 2 will be at $z > 4$ The combined method of using USS sources together with the $K - z$ diagram is extremely efficient in finding very high redshift radio galaxies This was shown by recent Keck II LRIS spectroscopy of two objects with $K = 19\ 75$ and $K = 19\ 70$, which yielded $z = 3\ 506$ and $z = 3\ 517$, respectively

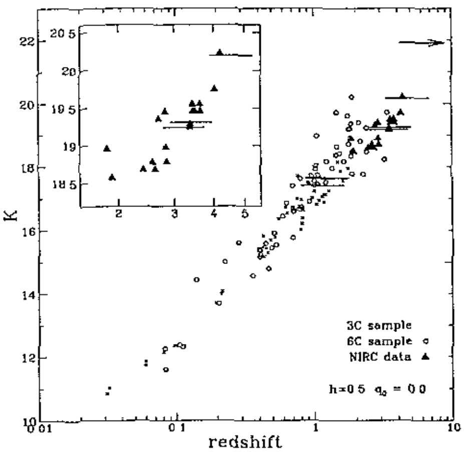

Figure 2. Hubble K-z diagram for the 3C and 6C surveys (Eales *et al* 1997), and NIRC data for HzRGs from van Breugel *et al* (1998) The new USS K-band detections and very high redshift candidates are shown by horizontal bars at the predicted redshift The horizontal arrow indicates the range of predicted redshift for our faintest K-band object All magnitudes are corrected to a 64 kpc metric diameter, assuming $H_0 = 50$, $q_0 = 0$ The inset shows a blowup of the NIRC data in the $1\ 5 < z < 5\ 5$ and $17\ 5 < K < 20\ 5$ region

3 Discussion

3.1 Redshift – Spectral Index Relation

Figure 3 plots spectral index against redshift for 4 different samples of radio sources. The 3CR and MRC/1Jy surveys (dots and crosses) have no spectral index bias and show the spectral index – redshift correlation. This relation is due to a combination of k–correction and intrinsic spectral curvature of the radio spectra (Carilli *et al.* this volume and references therein). The 4C USS sample (Chambers *et al.* 1996, open circles, $\alpha_{178}^{1415} < -1$, median $z = 1.84$) shows a rather uniform redshift distribution of sources, from $z = 0.4$ to 3.8, which includes a dramatically higher percentage of HzRGs than the surveys without spectral index selection. The preliminary results of our WN/TN sample have shown that we are even more efficient in finding $z > 2$ sources than the 4C (Table 1). The major differences between our sample and the 4C are our steeper spectral index cut-off and our lower flux limit. We interpret the higher median redshift in our sample as a combination of two effects: (i) an extension of the redshift – spectral index relation towards steeper spectral–indices, and (ii) our lower flux density limit causing the objects in our $S_{1400} > 10$ mJy flux–limited sample to be more distant than the $S_{178} > 2$ Jy 4C sample.

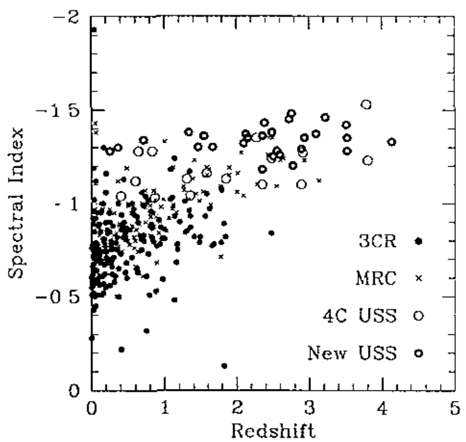

Figure 3. α_{1400}^{325} against z for 2 samples without spectral index selection (3CR and MRC; dots and crosses), and 2 USS samples (4C and our new new WN/TN sample; open circles and suns). Note that the correlation is present in the 3CR and MRC, and that the USS samples are finding much more $z > 2$ radio galaxies.

Sample	Definition	Known Redshift			Unknown
		$z < 2$	$2 < z < 3$	$z > 3$	
3CR	$S_{178} > 10$ Jy	99 5 %	0 5 %	0 %	1%
MRC/1Jy	$S_{408} > 0\ 95$ Jy	93 4 %	5 9 %	0 7 %	41 %
4C USS	$\alpha_{178}^{1414} < -1\ 0$	53 %	35 %	12 %	50 %
New USS	$\alpha_{325}^{1400} < -1\ 3$	35 %	35 %	30 %	45% (faint)

Table 1. The HzRG content for four samples of radio sources as a function of z: 3CR (Spinrad *et al* 1985), MRC/1Jy (McCarthy *et al* 1996), 4C (Chambers *et al* 1996), and our new USS sample

3.2 Radio Powers

The main advantage of using radio galaxies instead of quasars to study the formation of giant ellipticals is their host galaxy is much less contaminated by a non-stellar AGN However, also radio galaxies have a residual contribution of non-stellar light from the central AGN, confusing our view of the stellar population (Eales, this volume) A direct indication of this dependence is the correlation between emission-line luminosity and radio power (McCarthy 1993) The key to minimizing the effects of radio AGN activity is therefore to probe lower powers, which we achieve with the much lower flux density limit of our sample Figure 4 shows that we are indeed beginning to find galaxies at these lower powers The new galaxies at $z > 2$ with $P_{325} \lesssim 10^{28}$ W/Hz/sr will allow us to disentangle the redshift and power evolution of radio galaxies, with the caveat of using primarily USS sources

4 Conclusions

The new radio surveys have allowed us to define a sample of faint ($S_{1400} > 10$ mJy) sources with $\alpha < -1\ 3$ We have found relatively more $z > 2$ sources than previous USS or other surveys, indicating that the $z - \alpha$ relation extends out to higher redshifts The fraction of $z < 2$ galaxies is less than 1/3, confirming the high efficiency of the USS selection technique Stellar age estimates of the parent ellipticals of HzRGs all indicate formation redshifts $z_F > 5$ (*e g* Dunlop *et al* 1996) Our Near IR-imaging and deep spectroscopy at Keck provides the best chance of finding these $z > 5$ HzRGs and glimpse the earliest evolutionary stages of massive ellipticals

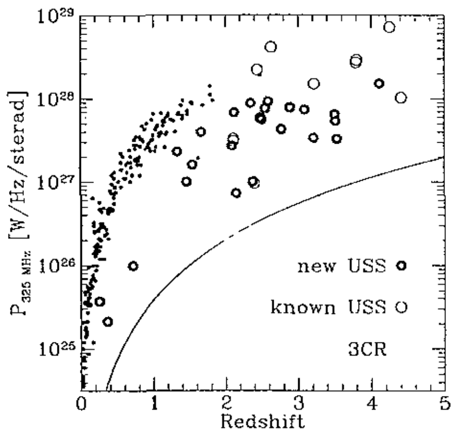

Figure 4. The monochromatic radio powei P_{325} against iedshift for 3CR and oui sample Known WN/TN sources aie pieviously known $z > 2$ radio galaxies falling into our sample The line indicates the lowei limit of our WN sample Our sample not only ieaches highei redshifts, but also selects souices with 10 to 15 times lower radio powers

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