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 cut-off of $\alpha < -1.3$ ($S \propto \nu^\alpha$) from the WENSS, NVSS and TEXAS surveys. Our first results for 27 sources show that we are almost twice as effective in finding HZRGs than surveys of relatively bright radio sources with a spectral index cut-off of $\alpha < -1.0$. 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. Our search is aimed at 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

High Redshift Radio Galaxies (HZRGs) have significantly contributed to our understanding of the formation of galaxies and their environments (McCarthy et al., 1993). 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, using HST and Keck. A dramatic example of this is the recent discovery of jet-induced star formation in the HZRG 4C41.17 at $z = 3.8$ (Dey et al., 1997; van Breugel et al., 1997), and the discovery of fully formed HZRG ellipticals at $z = 2.5$ (van Breugel et al., 1997).

Unfortunately, the number of known HZRGs dramatically decreases at high redshift (Figure 1). At present, 120 Radio Galaxies are known with $z > 2$, of which 16 have $z > 3$ and only 3 have $z > 4$. Determining redshifts of large numbers of
radio sources is very demanding in telescope time. Samples of optically faint radio sources therefore have to be limited, thereby unavoidably introducing selection effects.

To obtain significant samples of HZRGs, two main strategies have been used in the past: (i) surveys of a restricted part of the sky using a low flux density cut-off; (ii) all-sky surveys with a radio spectral index or radio-‘colour’ bias. The first major search for HZRGs was the 3CR survey, which now has complete redshift information (Spinrad et al., 1985; Rawlings et al., 1996a). This survey is biased as it only includes sources of extreme radio power ($S_{151} > 10\, \text{Jy}$), imposing a tight redshift-power relation, which makes it difficult to disentangle redshift and power dependence (e.g. Best, Rawlings, these proceedings). A southern equivalent to this 3CR survey, but 10 times deeper, is the Molonglo Reference Catalog/1 Jy survey (McCarthy et al., 1996). In finding very high redshift radio galaxies, the MRC/1Jy is not efficient, as $<1\%$ of the galaxies are at $z > 3$. A similar survey, the 6C/B2 is being undertaken in the northern hemisphere (Rawlings, these proceedings; Eales et al., 1997).

More effective searches for HZRGs have been made using with samples of Ultra Steep Spectrum (USS; $\alpha < -1$) radio sources covering a large sky area. Several samples of USS sources (Chambers et al., 1996; Röttgering et al., 1994) have led to the discovery of more than 70 $z > 2$ radio galaxies, more than half of the 120 known today. Figure 1 shows the contribution of USS selected sources (shaded) to the total number of $z > 2$ HZRGs. All the highest redshift radio galaxies ($z > 3.5$) have been found using USS criteria.

2. The sample of USS sources from the WENSS, NVSS and FIRST

With the advent of the WENSS, NVSS and FIRST surveys it is now possible for the first time to define a uniformly selected sample of USS sources covering the entire sky North of declination $-40^\circ$, and using 10 – 100 times lower flux density limits than has been possible before.
2.1. THE WENSS/NVSS (WN) SAMPLE

A correlation of 1997 March versions of the WENSS and NVSS catalogues provided spectral indices for 78,000 sources, of which we selected the 1% with spectral indices $\alpha_{1400}^{325} < -1.3$. Several additional cut-offs were applied to the sample: (i) $S_{1400} > 10$ mJy, to obtain a complete sample with spectral indices accurate to 0.1; (ii) galactic latitude $b > 15^\circ$, to avoid excessive galactic extinction during optical imaging and spectroscopy; and (iii) only unresolved sources in the WENSS survey (resolution $54''$) were retained. Unlike some other USS samples (e.g. the 6C; Rawlings, these proceedings), we did not apply other size cut-offs, as HZRGs exist with angular sizes of $30''$ or more (our sample contains for example a $z = 3.215$ galaxy of $35''$; Bremer, these proceedings). The present WN sample consists of 284 USS sources.

2.2. THE TEXAS/NVSS (TN) SAMPLE

The WENSS survey covers the northern quarter of the sky. In order to extend our samples to the southern hemisphere, while still maintaining uniform sample, we correlated the TEXAS 365 MHz survey (Douglas et al., 1996) with the NVSS. Next to the same cut-offs as in the WN sample, we have also excluded sources of questionable fluxes or positions from the TEXAS catalogue (Douglas et al., 1996). Because we are including TEXAS sources down to the flux limit, the TN sample will only be $\sim 80%$ complete at $S_{365} = 250$ mJy. As a result, the TN sample goes 4 times less deep than the WN sample. In the area covered by both WENSS and TEXAS, we therefore preferred the WENSS fluxes. Our TN sample covers $-40^\circ < \delta < 28^\circ$. We estimated the errors in the TN spectral indices by comparing them with the WN spectral indices in the overlapping region. We found that there is no systematic difference between TN and WN spectral indices as a function of WENSS flux density.

2.3. HIGH-RESOLUTION RADIO IMAGES FROM FIRST AND VLA OBSERVATIONS

Positional uncertainties of NVSS sources become larger as flux decreases (Condon, these proceedings). As we are reaching flux levels where these errors become $\sim 3''$, and virtually all our objects are fainter than $m_R = 20$, the NVSS position accuracy is inadequate for optical identifications. We therefore correlated our WN sample with the FIRST catalogue (Becker et al., 1995) which has accurate positions, and provides a check of the 1.4 GHz flux density, allowing us to weed out variable sources. Unfortunately, the present coverage of the FIRST survey overlaps with only 25% 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. Observations were done at 4.8 GHz to increase the resolution relative to the FIRST survey and to identify spectral curvature.
2.4. OPTICAL SPECTROSCOPY

The first year of spectroscopic observations of our sample using 3 – 4 m class telescopes has yielded firm redshifts for 27 sources. The median redshift is \( z = 2.38 \); only 8 have \( z < 2 \), while 15 have \( 2 < z < 3 \), 3 have \( 3 < z < 4 \), and 1 recently discovered has \( z = 4.11 \). For almost 40% of the sources observed, we could not yet determine the redshift because either no object or no emission lines were detected. We will attempt to obtain redshifts of these extremely high redshift candidates using larger aperture telescopes. An indication that these objects are indeed that distant is the \( K > 20.5 \) limit we found for 2 of them, suggesting redshifts significantly beyond \( z = 4 \) on the basis of the \( K-z \) relation.

3. Discussion

3.1. REDSHIFT – SPECTRAL INDEX RELATION

Figure 2 plots spectral index against redshift for 4 different samples of radio sources. The 3CR and MRC surveys (dots and crosses) have no spectral index bias, but still 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, in preparation). The 4C sample (open circles; \( \alpha_{1415} < -1 \); 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 bias. The initial 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. The higher median redshift in our sample can be interpreted 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.

| TABLE 1. Efficiencies in finding HZRGs |
|----------------------------------------|
| Known Redshift | Unknown |
| \( z < 2 \) | \( 2 < z < 3 \) | \( z > 3 \) |
| 3CR | 99.5 % | 0.5 % | 0 % | 0 % |
| MRC | 89.4 % | 16 % | 0.6 % | 40 % |
| B2/6C | 87.7 % | 8.8 % | 3.5 % | 10 % |
| 4C | 53 % | 35 % | 12 % | 50 % |
| WN/TN | 30 % | 55 % | 15 % | 40 % (faint) |
3.2. RADIO POWERS

The advantages of using radio galaxies instead of quasars to study the formation of giant ellipticals are their much large angular sizes and much fainter 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 (Rawlings, these proceedings). A direct indication of this dependence is the correlation between emission-line luminosity and radio power (McCarthy et al., 1993). Our initial results also show a rather weak correlation between the Ly-α luminosity and radio power. 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 3 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 at high redshift.

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 more $z > 2$ sources than previous USS or other surveys, indicating the $z - \alpha$ relation extends out to higher redshifts. The fraction of $z < 2$ galaxies is less than $1/3$, indicating we are near the peak efficiency
of the USS technique. Stellar age estimates of the parent ellipticals of HZRGs all indicate formation redshifts $z_F > 5$. The 40% of our sources that have remained undetected with 3–4m class telescopes are prime targets for finding these.

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References

Becker, R., White, R., Helfand, D., 1995, ApJ 450, 559.
Chambers, K., Miley, G., van Breugel, W., & Huang, J., 1996, ApJS 106, 215.
Dey, A. et al. 1997, in preparation
Douglas, J., Bask, F., Bozyan, F., Torrence, G., & Wolfe, C., 1996, AJ 111, 1945.
Eales, S., Rawlings, S., Law-Green, D., Cotter, G., & Lacy, M., 1997, MNRAS, astro-ph 9701023.
McCarthy, P., 1993, ARA&A 31, 639.
McCarthy, P., Kapahi, V., van Breugel, W., Persson, S., Athreya, R., & Subrahmanya, C., 1996, ApJS 107, 19.
Rawlings, S., Lacy, M. Leahy, J., Dunlop, J., Garrington, S. & Ludke, E., 1996, MNRAS 279, 13.
Röttgering, H., Lacy, M., Miley, G., Chambers, K., Saunders, R., 1994, A&AS 108, 79.
Spinrad, H., Djorgovski, S., Marr, J, & Aguilar, L., 1985, PASP 97, 932.
van Breugel, W. et al., 1997, in preparation
van Breugel, W. et al., 1997, in preparation