A Complete Sample of Millijansky Radio Sources

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Abstract.

The results of an optical and infrared investigation of a radio sample drawn from the 1.4 GHz Leiden-Berkeley Deep Survey are presented. This is believed to be the most comprehensive sample of radio sources at millijansky flux limits that is currently available. Optical counterparts have been identified for all but four sources in the two Hercules fields, and 80% of them are identified in the near-infrared. Redshifts have been obtained for 49 of the identified sources, and photometric redshifts were computed from the griK data for the remaining 20.

The general properties of the sample are summarized. The use of this sample in measuring the 1.4 GHz radio luminosity function is discussed. Finally, HST/NICMOS images of two old, red galaxies at $z \simeq 1.5$ are presented which show that both galaxies are dominated by an $r^{1/4}$ profile with a scale-length of 5 kpc.

1. The sample

The Leiden-Berkeley Deep Survey ('LBDS') consists of nine high latitude fields in the selected areas SA28, SA57, SA68 and an area in Hercules. They were surveyed with the Westerbork Synthesis Radio Telescope at 21 cm (1.412 GHz), reaching a 5-$\sigma$ limiting flux density of 1 mJy (Windhorst et al. 1984a). Multicolor prime focus photographic plates of the fields were used to find optical counterparts to the radio sources. Identifications were found for 53% of the sources in the full survey, whilst for the Hercules fields 47 out of 73 sources were identified (Windhorst et al. 1984b; Kron et al. 1985).

The Hercules fields were subsequently observed on the 200 inch Hale Telescope at Palomar Observatory between 1984 and 1988. Multiple observations were made through Gunn g, r and i filters over six runs. After processing and stacking of the multiple-epoch images, optical counterparts for 22 of the sources were found, leaving only four sources unidentified to $r \simeq 26$. Near-infrared observations have been made of the entire subsample at K, yielding 60/73 detections down to K $\simeq 19–21$. Half of the sources have been observed in H and approximately one-third in J. Observations of the brighter sources were made by Thuan et al. (1984) and by Neugebauer et al. and Katgert et al. (priv. comm.). K-band observations of the sample were completed by the present author and collaborators at the UK Infrared Telescope.
Prior to the start of the current work, only 16 of the 73 sources in the LBDS Hercules fields had redshifts published in the literature. Another 16 sources had unpublished redshifts. The author and collaborators have successfully observed a further 17 sources during the past few years, using both the 4.2 m William Herschel Telescope (Waddington 1999) and the 10 m Keck Telescope (Dunlop et al. 1996; Spinrad et al. 1997; Dey 1997). This brings the total number of spectroscopic redshifts to 49 out of 73 sources (67%). Photometric redshifts were calculated for the remaining one-third of the sample, using the spectral population synthesis models of Jimenez et al. (1998).

2. The 1.4 GHz radio luminosity function

Dunlop & Peacock (1990) used a sample of radio sources brighter than 0.1 Jy at 2.7 GHz to investigate the evolution of the radio luminosity function (RLF). They concluded that the comoving density of both flat- and steep-spectrum sources suffers a cut-off at redshifts \( z \simeq 2–4 \). This conclusion was drawn from the behavior of both free-form and simple parametric models (PLE/LDE), and the model-independent, banded \( V/V_{\text{max}} \) test. However, the results were crucially dependent upon the accuracy of their redshift estimates in the Parkes Selected Regions (PSR).

Figure 1 compares the flux limits of the LBDS with those of the PSR and 3C surveys. It is seen how the LBDS can be used to: (i) probe the faint end of the RLF out to much greater redshifts than the brighter surveys; and (ii)
Figure 2. HST/NICMOS F110W images and surface brightness profiles for 53W069 at \( z = 1.432 \) [left] and 53W091 at \( z = 1.552 \) [right]. The images are 3” on a side. Solid lines are the best-fitting model profiles convolved with the NICMOS PSF. AB magnitudes are used.

detect powerful radio galaxies out to very high redshifts (\( \gtrsim 10 \)). Thus we are able to use this millijansky sample to test the reality of the redshift cut-off. In figure 1b the cumulative redshift distribution of the LBDS Hercules sample (only those sources with \( S_{1.4} \geq 2 \) mJy) is compared with the predictions of Dunlop & Peacock (1990). It is seen that two of the free-form models (FF-4 and FF-5) provide a reasonable fit to the data over all redshifts, suggesting that the high-\( z \) decline in the RLF is real. The “bump” in the best-fit histogram at \( 0.4 \lesssim z \lesssim 1 \) is due to two spikes in the redshift distribution, that may be the result of possible large-scale structures (sheets) along the line of sight.

However, a more detailed investigation of the RLF reveals that the luminosity dependence of the data does not agree with the models. The observed RLF shows some indication that it turns over at \( z \simeq 0.5–1.5 \), and that the redshift of this cut-off is a function of the radio luminosity. The small number of sources makes it difficult to separate the redshift and luminosity dependence of the RLF sufficiently to be certain of this trend, but work is ongoing to improve the modeling of the data.

3. Surface brightness profiles of two old galaxies

Two of the most interesting individual sources in the sample are 53W069 and 53W091. Keck spectra of these galaxies revealed that their restframe ultraviolet light was dominated by old stellar populations at ages of 4.5 Gyr at \( z = 1.432 \) and 3.5 Gyr at \( z = 1.552 \) respectively (Dey 1997; Spinrad et al. 1997). Although there continues to be some debate over the accuracy of these ages, there can be little dispute that they are two of the oldest galaxies observed at that redshift.

An important corollary to investigate was whether these galaxies were also dynamically old objects. Peacock et al. (1998) showed that in order for the number density of these objects to be consistent with the evolving power spectrum of primordial density fluctuations, then the galaxies must be 3–4 Gyr old at \( z \simeq 1.5 \), having collapsed at \( z \simeq 6–8 \). This result is independent of the ages of the sources derived from their Keck spectra. Further clues to the dynamical history of the two galaxies can be gained by looking at their morphologies. 53W069 and 53W091 were observed using WFPC2 and NICMOS on the Hubble Space Telescope in Cycle 7 (Waddington et al. 1999). Data were collected in
F814W and F110W: these filters bridge the 4000 Å break and are thus most sensitive to the young and old stars in a galaxy respectively. Figure 2 shows the F110W images and surface brightness profiles for the two objects.

53W069 has a regular de Vaucouleurs $r^{1/4}$ profile, with an effective radius of 0′′.5 or 4 kpc ($H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 0.2$, $\Lambda = 0$). 53W091 is similarly dominated by an $r^{1/4}$ profile of effective radius 0′′.5 (4 kpc), however there is an additional component required to fit this galaxy. The form of this extra emission has not been unambiguously identified, but initial results suggest that it is consistent with an exponential profile of 0′′.2 (2 kpc) scale-length, contributing $\sim 40\%$ of the F110W flux within a 1′′.5 diameter aperture.

The spectrum of 53W091 can be modeled by adding a young stellar population to the spectrum of 53W069. Similarly the surface brightness profile of 53W091 can be modeled by adding an exponential component to the profile of 53W069. A possible interpretation is that 53W091 has a star-forming disk-like structure surrounding an otherwise passively evolving elliptical galaxy, such as 53W069.

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References

Dey, A. 1997, “The Hubble Space Telescope and the High Redshift Universe”, N. Tanvir et al. (eds), World Scientific, p. 373
Dunlop, J.S., Peacock, J. A., Spinrad, H., Dey, A., Jimenez, R., Stern, D., Windhorst, R. A. 1996, Nature, 381, 581
Jimenez, R., Dunlop, J. S., Peacock, J. A., Padoan, P., MacDonald, J., Jørgensen, U. G. 1999, MNRAS, submitted
Kron, R. G., Koo, D. C., Windhorst, R. A. 1985, A&A, 146, 38
Peacock, J. A., Jimenez, R., Dunlop, J. S., Waddington, I., Spinrad, H., Stern, D., Dey, A., Windhorst, R. A. 1998, MNRAS, 296, 1089
Spinrad, H., Dey, A., Stern, D., Dunlop, J. S., Peacock, J. A., Jimenez, R., Windhorst, R. A. 1997, ApJ, 484, 581
Thuan, T. X., Windhorst, R. A., Puschell, J. J., Isaacman, R. B., Owen, F. N. 1984, ApJ, 285, 515
Waddington, I. 1999, PhD Thesis, University of Edinburgh
Waddington, I., Windhorst, R. A., Peacock, J. A., Dunlop, J. S., Cohen, S. H., McClure, R. 1999, in preparation
Windhorst, R. A., van Heerde, G. M., Katgert, P. 1984a, A&AS, 58, 1
Windhorst, R. A., Kron, R. G., Koo, D. C. 1984b, A&AS, 58, 39