THE PHOENIX DEEP SURVEY: 
A Deep Microjansky Radio Survey

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Abstract

The study of the nature of faint radio sources is of great importance since a significant fraction of these objects is thought to be composed of actively star-forming galaxies. Due to the increased sensitivity of radio telescopes, we are now not only able to catalogue large numbers of these sources in the sub-millijansky regime, but also to start the study of the nature of increasingly fainter microjansky sources.

This paper presents a new very deep 1.4 GHz radio survey made as a part of the Phoenix Deep Survey, a project aimed to study the nature of the faintest radio sources. With a limiting sensitivity of 45 \( \mu \)Jy, this new survey has allowed us to assemble a large number of sources with 1.4 GHz flux densities below 100 \( \mu \)Jy. The resulting source counts and the analysis of the optical properties of the faintest radio sources is presented.

1 Introduction

Deep radio surveys are dominated, at sub-millijansky levels, by a population of actively star-forming galaxies out to \( z \sim 1 \). This sub-millijansky population was first revealed by the changing slope of the 1.4 GHz radio source counts below \( \sim 5 \) mJy (e.g. [12]). Spectroscopic and photometric follow-up studies ([2], [1]) have revealed a population of optically blue galaxies, often exhibiting perturbed morphologies indicative of interactions, with spectra similar to those of the star-forming IRAS galaxies. Moreover, the study of their luminosity function has revealed that these sources have undergone strong luminosity evolution, possibly induced by interactions and mergers ([7], [10]). However, it has been hinted that at the microjansky level radio sources could be related to AGN activity rather than star formation ([8]) and even at higher radio levels the matter is not completely settled ([8]). The assembly of large samples of these sources, down to the microjansky level, is essential to clarify the issue.

It is nevertheless clear that deep radio surveys can assemble large numbers of the most active star-forming galaxies out to \( z \sim 1 \). The fact that 1.4 GHz radiation can be used to determine star formation rates in star-forming galaxies ([3]), with several advantages over alternative methods (insensitivity to dust absorption, unlike the optical and ultraviolet indicators, and superior sensitivity and astrometric precision over millimeter-wave and far-infrared indicators, thus allowing direct optical identifications) shows that deep radio surveys can lead to important studies on galaxy evolution and the global star-formation rate history.
Here we present one of the faintest radio surveys made so far at 1.4 GHz. Covering a wide 50' diameter region, this has allowed us to assemble a large sample of sub-mJy and microjansky 1.4 GHz radio sources. Using R-band CCD images, we also present a preliminary analysis of the optical counterparts of the faintest radio objects.

2 1.4 GHz Radio observations and source counts

The Phoenix Deep Survey project is a collaboration between Imperial College and the University of Sydney, aimed to study the nature and statistical properties of the faint radio population, through deep multiwavelength observations. The radio survey is carried out at 1.4 GHz and covers an area of 3.1 square degrees (the Phoenix Deep Field – PDF). Previous observations resulted in images with a 5σ sensitivity of 300 µJy and 100 µJy in a smaller 36' diameter sub-region (the Phoenix Deep Field Sub-region – PDFS). Recently, a 1° diameter region centered on the PDFS was observed using the Australia Telescope Compact Array (ATCA) in its 6C configuration. Details on the data reduction are presented elsewhere ([1], [8]). The resulting ultra-deep survey incorporates a total of 164 hours of observation. On the final natural weighted image the RMS noise increases uniformly from 9 µJy at the center to 25 µJy at a radius of 25', the limit of the chosen area to perform source detection.

A total of 773 sources with a peak flux density greater than the local 4σ value survived visual inspection. Integrated fluxes ($S_{1.4}$) range from 45 µJy to 23 mJy with 187 sources having $S_{1.4}$<100 µJy. The flux distribution of the sub-mJy and microjansky sources detected is presented in Figure 1a.

The radio source counts were constructed and are presented in Figure 1b, along with data from other surveys (the counts from previous work on the PDF and PDFS ([9]), a compilation of data from ([9]) and the source counts from the 1.4 GHz ATCA observations of the Hubble Deep Field South (HDF-S) ([10]). The solid and dashed lines represent source count predictions assuming a mixed AGN and starburst population ([9]). The best fit was achieved assuming a luminosity evolution ($L(z) \propto (1+z)^Q$) for the starburst population at rates corresponding to $Q = 3.3$ (solid line). The $Q = 2.5$ and 4.1 models are also shown (lower and upper dashed lines respectively). It can be seen that the models continue to provide a good fit to the observed source counts down to the 50 µJy flux level. It must be noted that these models predict that the majority of the sources below $\sim 200$ µJy (down to a few microjansky) will be starburst galaxies.

![Figure 1: a) Radio flux distribution for the sub-mJy and microjansky sources detected and b) the normalized differential 1.4 GHz source counts for the present radio survey, along with data from other surveys and radio source count models – see text for details.](image-url)
3 Optical counterparts of the microjansky sources

The optical photometric observations of this field were carried out with the Anglo-Australian Telescope (AAT) and consist of prime-focus CCD observations made in the Johnson-Kron-Cousins $R$-band, with a completeness limit of $R=22.5$. A detailed account of the optical observations and data reduction is given in [4].

The most probable optical association to a given radio source was chosen by searching a radius of $5''$ around it and selecting the optical source with the smallest probability of being an accidental alignment (given the known surface density of sources as bright or brighter than the candidate), if less than 5%. Of the 773 detected radio sources, 52% have optical counterparts. Table 1 summarizes the analysis of the optical counterparts of these sources.

| $S_{1.4} (\mu Jy)$ | ID rate (%) | $R_{med}$ |
|-------------------|-------------|-----------|
| 200–800           | 56          | 20.1      |
| 100–200           | 55          | 20.3      |
| 45–100            | 44          | 21.2      |

Both the identification rate and the median $R$ magnitude are seen to decrease for flux densities $S_{1.4}<100 \mu Jy$. Also, most of the sources with radio fluxes below this level are identified with single optical galaxies, rather than interacting systems (see examples in Figure 2), unlike those above this limit. This may reflect the fact that these identifications are made quite close to the limit of the CCD images, or it may indicate that the very faint radio sources are located in galaxies different from those harboring slightly brighter sub-mJy radio sources. Deeper optical imaging of these sources is needed to clarify this issue.

Figure 2: Examples of the optical counterparts of the microjansky sources detected in the present survey. The contours correspond to the 1.4 GHz emission. The integrated radio fluxes of the sources indicated by the arrows are, from left to right, $S_{1.4} = 95$, 96 and 48 $\mu Jy$.

4 Conclusions

A new ultra deep radio survey is presented. The sample of faint radio sources assembled, with $S_{1.4}>45 \mu Jy$, is homogeneously selected and constitutes a uniform survey across the entire
flux density range. This sample is being used to study a large number of the faintest radio sources through multicolour photometry and spectroscopy.

The source counts were built and, down to the 50 $\mu$Jy level, are seen to be consistent with radio source count models that imply a majority of starburst galaxies below $\sim$200 $\mu$Jy.

A significant number of sources with 1.4 GHz fluxes below 100$\mu$Jy were detected and the analysis of their optical counterparts show that the optical magnitude of these sources is lower than that for the (radio) brighter sub-mJy population. Also, they are mostly identified with single optical galaxies, although this may reflect the relatively bright optical magnitude limit of the present survey.

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References

[1] Afonso, J.M., Mobasher, B., Hopkins, A. & Cram, L. 1999, Astroph. & Space Science , submitted
[2] Benn, C.R., Rowan-Robinson M., McMahon, R.G., Broadhurst, T.J.& Lawrence, A. 1993, MNRAS 263, 98
[3] Cram, L., Hopkins, A., Mobasher, B. & Rowan-Robinson, M. 1998, Astrophys. J. 507, 155
[4] Georgakakis, A., Mobasher, B., Cram, L., Hopkins, A., Lidman, C. & Rowan-Robinson, M. 1999, MNRAS , in press (astro-ph/9903016)
[5] Gruppioni, C., Mignoli, M. & Zamorani, G. 1999, MNRAS 304, 199
[6] Hammer, F., Crampton, D., Lilly, S., Le Fèvre, O. & Kenet, T. 1995, MNRAS 276, 1085
[7] Hopkins, A.M., Mobasher, B., Cram, L. & Rowan-Robinson, M. 1998, MNRAS 296, 839
[8] Hopkins, A., Afonso, J., Cram, L. & Mobasher, B. 1999, Astrophys. J. Letters, in press (astro-ph/9905055)
[9] Norris, R., Hopkins, A., Sault, R., Ekers, R., Ekers, J., Badia, F., Higdon, J., Wieringa, M., Boyle, B., 1999, in preparation
[10] Rowan-Robinson M., Benn, C.R., Lawrence, A., McMahon, R.G. & Broadhurst, T.J. 1993, MNRAS 263, 123
[11] Thuan, T.X., Patterson, R.J., Condon, J.J. & Mitchell, K.J. 1992, Astron. J. 104, 1331
[12] Windhorst, R.A., Miley, G.K., Owen, F.N., Kron, R.G. & Koo, D.C. 1985, Astrophys. J. 289, 494
[13] Windhorst, R.A., Fomalont, E.B., Partridge, R.B. & Lowenthal, J.D. 1993, Astrophys. J. 405, 498