

# Near-infrared $K$ –band imaging of a sample of Ultra-Steep-Spectrum radio sources selected at 74 MHz

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## ABSTRACT

In this paper we present near-infrared  $K$ –band imaging of a sample of ultra-steep spectrum (USS) radio sources selected at 74 MHz. The dual selection criteria of low frequency and USS means that we should be sensitive to the highest redshift ( $z > 5$ ) radio galaxies. We have obtained  $K$ –band magnitudes for all of the objects in our sample of 26 and discuss the properties of each.

There is a pronounced bias in this sample towards fainter magnitudes and thus higher redshifts when compared to complete unfiltered samples such as 7CRS (Willott et al. 2002), implying that the steep-spectrum technique is still viable at 74 MHz. However, there are more bright ( $K < 17$ ) sources in the 74 MHz sample than in a similar sample selected at 151 MHz, namely 6C\*. This is principally due to the additional selection criterion of a small angular size for the radio sources in 6C\*, four of the six sources in the 74 MHz USS sample with  $K < 17$  have angular sizes  $> 15$  arcsec (the angular size cutoff of 6C\*).

We find that the distribution of  $K$ -band magnitudes from a sample selected at 74 MHz is statistically indistinguishable from the 6C\* sample, when similar angular size filtering is applied to the 74 MHz sample.

**Key words:** galaxies:active - galaxies:nuclei - galaxies:evolution - radio continuum:galaxies - galaxies:high redshift

## 1 INTRODUCTION

The search for high-redshift radio galaxies has been somewhat overshadowed in recent years by the discovery of significant numbers of radio-quiet quasars from the Sloan Digital Sky Survey (e.g. Fan et al. 2003). However, the bright point-source nature of the quasars means it is extremely difficult to study the stellar populations of the host galaxies of these powerful active galactic nuclei (AGN). For this reason alone it is still useful to search for distant radio galaxies.

Furthermore, there are extremely important roles that radio galaxies may play in our understanding of general galaxy formation and evolution. First, the fact that they are selected via radio emission means that they are essentially free of selection effects inherent to optical surveys, such as dust obscuration, which may be more prevalent in the early Universe (e.g. Archibald et al. 2001), and particularly

around massive galaxies (Stevens et al. 2004). Second, in radio galaxies the powerful nuclear emission is obscured by the ‘dusty torus’ in orientation-based unification schemes, thus we have an uninhibited view of any neutral gas all the way up to the host galaxy, without the problem of the ionised Stromgren sphere along the line-of-sight which quasars suffer from. This means that the gas, which possibly helped in the formation of the galaxy and in fuelling the AGN, can be probed up to the vicinity of the host galaxy itself (e.g. Jarvis et al. 2003; Wilman et al. 2004). Third, if we discover powerful radio galaxies within the epoch of reionization we would be able to be able to probe the 21 cm forest at this important epoch in the history of the Universe (e.g. Carilli, Gnedin & Owen 2002). Fourth, it is also now known that powerful radio galaxies in the high-redshift Universe trace overdensities of galaxies (e.g. Venemans et al. 2002; Miley et al. 2004) which may go on to become the richest clusters in the nearby Universe and thus provide a probe of large-scale structure formation over all cosmic epochs. A fifth reason is

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that they are very luminous allowing for detailed studies of cold, warm and hot gas using millimetre, optical and x-ray telescopes (e.g. Stevens et al. 2004; Villar-Martín et al. 2003; Carilli 2003).

In the past decade the search for radio galaxies at the highest redshifts has been optimized using various selection techniques. The most widely used of these is that of a steep-radio-spectral index. This works because radio spectra are generally concave, thus they steepen at high frequencies, this is particular true at the highest redshifts where the inverse Compton losses, due to the increase in temperature of the cosmic microwave background, are higher. Further, the observed rest frame frequencies are higher for high-redshift sources. Therefore, by filtering a sample to include just those sources with steep spectral indices one would expect to select in favour of high redshift objects. This idea has in fact been verified by several groups (e.g. Blundell et al. 1998; De Breuck et al. 2000, 2001; Jarvis et al. 2001a,b).

Another important radio selection criteria is that of low frequency. This is because the spectra of the highest redshift sources are redshifted towards low frequency, thus the bulk of the flux from the source itself, although emitted at higher frequencies is observed at much lower frequencies, and this effect obviously increases with redshift. Thus the majority of surveys for high redshift radio galaxies have taken place at frequencies  $\ll 1$  GHz, the two most prominent being 325 MHz (De Breuck et al. 2000, 2001) and 151 MHz (Blundell et al. 1998; Jarvis et al. 2001a,b), which have found the highest redshift radio galaxies to date (Rawlings et al. 1996; van Breugel et al. 1999). Low-frequency selection also preferentially selects the optically thin lobe emission, which is independent of orientation, unlike high-frequency selection which preferentially selects the optically thick emission from the core of the AGN, which means that low-frequency surveys are crucial for unification studies (e.g. Willott et al. 2000). The next step in this type of survey would be to push the observed frequency lower.

The new 74 MHz system on the Very Large Array (VLA), fully implemented in 1998 (Kassim et al. 1993), has opened up a new window into the previously unexplored regime of very low-frequency radio observations at high sensitivity and sub-arcminute resolution. Therefore, we have initiated a survey at this low frequency, with steep-spectral index selection, to continue the search for the highest-redshift radio galaxies. The radio data for this survey are described in Cohen et al. (2004), and has  $\sim 10$  times the resolution and sensitivity of 8C. In this paper we present our near-infrared  $K$ -band follow-up observations of all the steep-spectrum sources in this sample.

The paper is set out as follows, in section 2 we summarize how the sample was selected and in section 3 we describe the  $K$ -band observations which are then presented in section 4. In section 5 we compare the distribution of  $K$ -band magnitude with similar samples selected at higher frequencies and in section 6 we discuss our results.

## 2 SAMPLE SELECTION

Full details of how the sample was selected can be found in Cohen et al. (2004). For clarity we summarise the selection criteria here.

- $S_{74\text{MHz}} \geq 0.1$  Jy. This is a lower limit as the sensitivity is a function of position on the sky, due to areas of higher noise. We refer the reader to Cohen et al. (2004) for full details.

- Spectral index between 74 MHz and 1400 MHz  $\alpha_{74}^{1400} < -1.2$ , where  $S_\nu \propto \nu^\alpha$ . The NRAO VLA Sky Survey (NVSS; Condon et al. 1998) was used to measure the 1400 MHz flux densities as the low-angular resolution ( $\sim 40$  arcsec) is well matched to that of the 74 MHz observations ( $\sim 25$  arcsec), therefore we do not expect any extended structure to be resolved out in either survey.

This leads to a sample of 26 sources detected over a total area of 0.05 sr.

## 3 $K$ -band IMAGING

### 3.1 Observations

The  $K$ -band ( $2.2\mu\text{m}$ ) imaging of the 74 MHz USS sample was made over several flexibly scheduled runs at the United Kingdom Infrared Telescope (UKIRT), beginning in Dec 2003 up to March 2004. The observations were made using the high-resolution infrared camera on UKIRT, UFTI (UKIRT Fast-Track Imager), which comprises a  $1024 \times 1024$  HgCdTe array, with a plate scale of  $0.091$  arcsec pixel $^{-1}$ , giving a field of view of  $92 \times 92$  arcsec $^2$ . All observations were made in photometric conditions, with seeing always  $< 0.6$  arcsec, with the tip-tilt system.

In order to subtract the rapidly changing sky background at these wavelengths, to provide a good flat-field and to minimise the effects of cosmic ray contamination and bad pixels, we used the standard observing strategy of off-setting the position of the telescope by  $\sim 10$  arcsec between each exposure. The offsets were arranged in a  $3 \times 3$  mosaic of nine exposures. The integration time varies between objects in the sample, with the fainter sources being observed for longer. A summary of all the  $K$ -band observations is given in Table 1.

### 3.2 Data reduction

The  $K$ -band images were reduced using standard procedures. We first subtracted the dark current from each image. We then divided by the normalised flat-field, created by combining the nine exposures of the particular field with a median filter, which removes any objects which appear in different positions on the chip over the nine exposures. To combine the individual images we registered all of the frames using a bright star which was present in each of the nine pointings. In the cases where there was no bright star in the images, the offsets recorded in the image headers were used to align the frames. The registered images were then combined using an average clipping procedure to reject pixels more than  $4\sigma$  away from the median of the distribution.

Astrometry for each image was achieved by identifying sources in the image with objects in the POSS-II. In all cases, apart from J1252.7+2207, we were able to identify three or more sources on our images with objects on the finding charts, and in these cases the astrometry, performed with the KARMA-Koords task package (Gooch 1996; <http://www.atnf.csiro.au/computing/software/karma/>)

which performs a simple linear fit to the plate solution, and for UFTI this is typically accurate to  $\lesssim 1$  arcsec. Photometric calibration was performed using at least two UKIRT faint standard stars on each night where data were taken. The reduced images are shown in figure 1 with the Faint Images of the Radio Sky at Twenty centimetres (FIRST; Becker, White & Helfand 1995) radio contours overlaid. The FIRST survey was carried out at 1.4 GHz and has an angular resolution of  $\sim 5$  arcsec.

## 4 RESULTS

In Table 2 we present the *K*–band magnitudes for all of the sources in our 74 MHz USS sample. The magnitudes have been measured in three apertures of  $3''$ ,  $5''$  and  $8''$  respectively, both to allow ease of comparison with previous work and to make sure that a magnitude is given even when there is a nearby object which may increase the flux in one of the larger apertures.

### 4.1 Notes on Individual Sources

In this section we present notes on all of the individual sources in the 74 MHz USS sample. In the cases where there is an infrared counterpart within 1.5 arcsec (or within the positional uncertainty of the individual astrometerised images) of the core of a one-component radio source, or within 1.5 arcsec of the axis along a double-lobed source, we take this to be the true identification (ID) of the radio source host galaxy.

**J1225.0+2146** This source is double lobed with an extended *K*-band ID towards the western lobe. There are two plausible candidates for the ID which may be interacting, at  $\alpha = 12:25:02.40$ ,  $\delta = 21:46:52.6$  with  $K = 20.12$ , and  $\alpha = 12:25:02.51$ ,  $\delta = 21:46:54.5$  with  $K = 20.20$ . The entry in table 2 is the magnitude for the western most ID. There is also a faint infrared source at the centre of the western lobe ( $\alpha = 12:25:02.14$ ,  $\delta = 21:46:50.6$ ), with a *K*-band magnitude  $K > 21$ , this is unlikely to be the ID but could be enhanced emission due to the passage of the radio jet.

**J1226.3+2418** A large radio source with a secure ID at the centre of the brightest radio emission.

**J1228.9+3114** This source has a slightly extended radio morphology centred at  $\alpha = 12:28:59.58$ ,  $\delta = +31:14:57.6$ . There is a bright *K*-band counterpart to the north-east of this centroid at  $\alpha = 12:28:59.56$ ,  $\delta = +31:15:01.1$  which may be the host galaxy. However, this is not centred on the bright radio emission and it is possible that a true ID centred on the radio emission may be beyond the detection limit of our imaging observations at  $K > 20.7$  in a 3 arcsec aperture ( $3\sigma$ ).

**J1229.1+3040** This source is slightly extended in the radio map. We have a total of 3240 second integration with UKIRT on this source with no apparent ID down to a limiting  $3\sigma$  total magnitude of  $K = 20.7$  in a 3 arcsec aperture.

**J1229.9+3712** The radio morphology for this source is such that it could be the lobe of a larger source. Indeed, inspection of the FIRST radio maps does show three aligned components with a probable core at  $\alpha = 12:30:02.98$ ,  $\delta = 37:12:46.1$ . The full extent of this radio source on the sky is  $\sim 3$  arcmin. The FIRST radio map overplotted on

the Digitized Sky Survey *R*–band image is shown in figure 2. There is no bright ID detected in the POSS-II image at the position of the core.

**J1230.2+2326** This source has a double-lobed radio morphology with a bright *K*-band ID situated between them, along the radio axis.

**J1230.6+3247** An extended radio source with two *K*-band counterparts close to both of the bright radio components. This could be two distinct sources with both of the two infrared objects hosting an AGN (marked A and B in figure 1). We note that the peak centroid of the 74 MHz radio map is centred closer to the south-western component with the fainter *K*-band ID at  $\alpha = 12:30:37.96$ ,  $\delta = +32:47:18.2$  (referred to as J1230.6+3247A), and we consider this to be the most likely near-infrared counterpart.

**J1231.2+2538** Compact radio structure with a faint *K*-band ID at its centre.

**J1231.3+3724** A compact radio sources with a faint *K*-band ID at its centre.

**J1231.5+3236** This source has a very extended radio morphology with a *K*-band ID at its centre. There also seems to be an overdensity of radio sources close to the radio source, possibly indicative of a cluster.

**J1232.2+2814** Another compact radio source with a faint *K*-band ID at its centre.

**J1232.6+3157** A small but extended radio morphology with two bright *K*-band counterparts towards each of the extended components. This could be a superposition of two sources or one radio source with two plausible IDs, or alternatively it could be lensed. Spectroscopy will be needed to distinguish between these possibilities. The *K*-band magnitudes of both the northern object (J1232.6+3157N) and southern object (J1232.6+3157S) are given in tables 2 and 3. Given the similarity in *K*-band magnitude, the distribution in *K*-band magnitude of this sample is not affected significantly by choosing one counterpart over the other for this radio source.

**J1234.3+2605** A double-lobed radio source with a plausible *K*-band ID towards the eastern lobe. There is also a fainter *K*-band source at the centre of the eastern lobe at  $\alpha = 12:34:24.12$ ,  $\delta = 26:05:51.4$ , both are within 1.5 arcsec of the centre of the radio lobe and either could be the ID. We assume for this paper that the brighter source is the ID as it lies along the radio axis.

**J1238.2+2613** A compact radio sources with a *K*-band ID at its centre.

**J1238.8+3559** A double-lobed radio source with a bright *K*-band source at the centre of the radio structure, which we take to be the ID. There are also two further *K*-band sources stretching along the western lobe, which could be due to jet-induced star formation, although spectroscopy will be needed to confirm that these objects are at the same redshift as the radio source.

**J1243.7+2830** A compact radio structure with a *K*-band ID at its centre. There is also another *K*-band source of similar magnitude that may be interacting with this central galaxy  $\sim 1.3$  arcsec to the north-east.

**J1245.9+3320** A slightly extended radio source with a faint *K*-band ID at its centre.

**J1246.4+2516** A compact radio source with a faint *K*-band ID in the centre.

**Table 1.** Log of the  $K$ -band imaging observations for our 74 MHz USS sample.

| Source       | Dates Observed                              | Total exposure time / s |
|--------------|---|-------------------------|
| J1225.0+2146 | 2004-02-12                                  | 2700                    |
| J1226.3+2418 | 2004-01-19                                  | 540                     |
| J1228.9+3114 | 2003-12-24 2004-01-17 2004-01-19 2004-04-09 | 3240                    |
| J1229.1+3040 | 2003-12-24 2004-01-17 2004-01-19 2004-02-12 | 3240                    |
| J1229.9+3712 | 2003-12-24 2004-01-17                       | 1080                    |
| J1230.2+2326 | 2004-01-19                                  | 540                     |
| J1230.6+3247 | 2003-12-24                                  | 540                     |
| J1231.2+2538 | 2004-01-19 2004-02-13                       | 1620                    |
| J1231.3+3724 | 2004-01-17                                  | 540                     |
| J1231.5+3236 | 2004-01-17                                  | 540                     |
| J1232.2+2814 | 2004-01-17 2004-02-20                       | 2160                    |
| J1232.6+3157 | 2004-02-13                                  | 1080                    |
| J1234.3+2605 | 2004-01-17                                  | 540                     |
| J1238.2+2613 | 2004-01-17                                  | 540                     |
| J1238.8+3559 | 2004-01-17                                  | 540                     |
| J1243.7+2830 | 2004-01-17                                  | 540                     |
| J1245.9+3320 | 2004-02-20                                  | 540                     |
| J1246.4+2516 | 2004-01-17 2004-02-20                       | 1620                    |
| J1248.2+2747 | 2004-01-17                                  | 540                     |
| J1249.0+3615 | 2004-01-19                                  | 540                     |
| J1249.7+3408 | 2004-02-20 2004-02-27 2004-04-07            | 5400                    |
| J1250.4+2941 | 2004-01-17                                  | 540                     |
| J1252.7+2207 | 2004-01-17                                  | 540                     |
| J1253.4+2703 | 2004-01-17                                  | 540                     |
| J1253.6+2509 | 2004-01-17                                  | 540                     |
| J1256.9+2811 | 2004-01-17 2004-02-12                       | 2160                    |

**J1248.2+2747** This source has a slightly extended radio morphology with a fairly bright  $K$ -band ID close ( $\sim 1$  arcsec away) to the centre.

**J1249.0+3615** This is an extended radio source with a bright  $K$ -band ID at the centre of the brightest point in the radio emission, which we take to be the core. This galaxy has a very close possible companion  $\sim 1$  arcsec to the north with which it may be interacting. The 74 MHz centroid for this source is  $\sim 12$  arcsec to the north of the core position quoted here. This may be because the 74 MHz emission arises from a more extended, optically thin lobe.

**J1249.7+3408** A compact radio source with a very faint  $K$ -band ID at the centre. There are also three fainter sources in the immediate vicinity ( $< 6$  arcsec away) of the ID which may be associated with an overdensity of galaxies at high redshift (the  $K$ -band magnitude of this source means it is likely to be at  $z > 4$ ).

**J1250.4+2941** This source is a highly extended double-lobed radio source in the East-West direction. There is a bright ID at the centre of the source with a line of three fainter sources aligned along the western lobe. This is highly unlikely to be a chance alignment, therefore these three sources may be due to gas compression by the jet causing increased star formation, or could be due to a preferred orientation of galaxy overdensities with respect to the jet axis. Spectroscopy will be needed to confirm whether these are actually at the same redshift as the radio source.

**J1252.7+2207** This is a fairly compact source with a  $K$ -band ID near its centre. The astrometry on this image is only good to  $\sim 1.5$  arcsec, therefore it is very plausible that the ID is actually at the centre of the radio centroid.

**Figure 2.** POSS-II  $R$ -band image of J1229.9+3712. The contours represent the FIRST source which is almost certainly a large source extending to  $\sim 3$  arcmin. The 74 MHz USS source is situated at the position of the western lobe. The peak flux density of the radio emission is 18.60 mJy/beam, and the lowest contour is at 8 per cent this value, with increments of 15 per cent.

**J1253.4+2703** This source has a very unusual morphology in the radio, and in Cohen et al. (2004) we suggested that it could be a cluster relic. There is a bright  $K$ -band source near the centre of the radio emission but spectroscopy will be needed to confirm whether this is associated with the radio emission.

**J1253.6+2509** This is a double-lobed radio source with a  $K$ -band ID centred on the northern most extent of the southern lobe, along the axis of the radio emission.

**J1256.9+2811** This is a compact source with a very faint  $K$ -band ID consistent with being at its centre.

## 5 COMPARISON WITH OTHER SAMPLES

In this section we compare the distributions of  $K$ -band magnitude of the USS sample with the distribution of magnitudes from a similar survey selected at 151 MHz and also with a steep-spectrum filtering criteria, namely 6C\* (Jarvis et al. 2001a; 2001b). The  $K$ -band magnitudes can be used to estimate the redshift of a source given the observed tightness of the  $K - z$  relation (e.g. Jarvis et al. 2001b; Willott et al. 2003). Figure 3 shows the histogram of the  $K$ -band magnitudes for the USS sample and the 6C\* sample.

**Table 2.** *K*-band magnitudes for the 74 MHz USS sample in three different angular apertures. nbo denotes that the radio galaxy is too close to a nearby object to measure the magnitude reliably. J1229.9+3712 is not shown as it is now omitted from the sample because the 74 MHz emission is from the lobe of a larger source (Figure 2). † the quoted magnitudes are for the bright galaxy to the north east, the actual ID may not be visible in this image (see notes on this source).

| Source        | Magnitude from<br>3" diameter | Magnitude from<br>5" diameter | Magnitude from<br>8" diameter | Notes                               |
|---------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------------|
| J1225.0+2146  | 20.12 ± 0.33                  | 19.70 ± 0.32                  | 19.54 ± 0.32                  |                                     |
| J1226.3+2418  | 16.911 ± 0.087                | 16.764 ± 0.083                | 16.608 ± 0.080                |                                     |
| J1228.9+3114† | 16.502 ± 0.079                | 16.276 ± 0.073                | 16.073 ± 0.069                |                                     |
| J1229.1+3040  | > 20.7                        | > 20.2                        | > 19.7                        |                                     |
| J1230.2+2326  | 14.301 ± 0.026                | 13.922 ± 0.022                | 13.641 ± 0.019                |                                     |
| J1230.6+3247A | 19.681 ± 0.375                | 19.675 ± 0.406                | 19.655 ± 0.502                | ID on the western-most radio source |
| J1230.6+3247B | 17.979 ± 0.151                | 17.911 ± 0.156                | 17.512 ± 0.140                | ID on the radio source to the NE    |
| J1231.2+2538  | 19.187 ± 0.225                | 18.780 ± 0.195                | 18.759 ± 0.225                |                                     |
| J1231.3+3724  | 18.098 ± 0.170                | 17.870 ± 0.161                | 17.814 ± 0.177                |                                     |
| J1231.5+3236  | 17.499 ± 0.128                | 17.276 ± 0.119                | nbo                           |                                     |
| J1232.2+2814  | 19.313 ± 0.266                | 19.363 ± 0.292                | -                             |                                     |
| J1232.6+3157N | 17.512 ± 0.110                | 17.296 ± 0.101                | 17.151 ± 0.097                | north source                        |
| J1232.6+3157S | 17.376 ± 0.103                | 17.159 ± 0.094                | 16.726 ± 0.078                | south source                        |
| J1234.3+2605  | 18.585 ± 0.218                | 17.992 ± 0.173                | 17.786 ± 0.176                |                                     |
| J1238.2+2613  | 17.543 ± 0.130                | 17.521 ± 0.134                | 17.662 ± 0.162                |                                     |
| J1238.8+3559  | 16.961 ± 0.099                | 16.724 ± 0.091                | 16.522 ± 0.087                |                                     |
| J1243.7+2830  | 17.255 ± 0.113                | 16.996 ± 0.103                | 16.717 ± 0.096                | merger?                             |
| J1245.9+3320  | 18.405 ± 0.178                | 18.082 ± 0.162                | 17.695 ± 0.151                |                                     |
| J1246.4+2516  | 18.552 ± 0.187                | 18.507 ± 0.192                | 18.516 ± 0.223                |                                     |
| J1248.2+2747  | 17.672 ± 0.139                | 17.508 ± 0.134                | 17.413 ± 0.143                |                                     |
| J1249.0+3615  | 15.862 ± 0.054                | 15.607 ± 0.048                | 15.500 ± 0.047                | merger?                             |
| J1249.7+3408  | 20.093 ± 0.396                | 19.576 ± 0.320                | 19.483 ± 0.340                |                                     |
| J1250.4+2941  | 16.815 ± 0.092                | nbo                           | nbo                           |                                     |
| J1252.7+2207  | 17.856 ± 0.151                | 17.624 ± 0.142                | 17.447 ± 0.145                |                                     |
| J1253.4+2703  | 16.777 ± 0.090                | 16.592 ± 0.085                | 16.511 ± 0.087                |                                     |
| J1253.6+2509  | 18.674 ± 0.230                | 18.628 ± 0.258                | 18.503 ± 0.322                |                                     |
| J1256.9+2811  | 19.466 ± 0.288                | 19.224 ± 0.272                | 18.885 ± 0.257                |                                     |

**Figure 1.** *K*-band images (greyscale) of the 26 USS sources from our 74 MHz sample. The images have been smoothed for presentation purposes. The black contours represent the radio maps from the 1.4 GHz FIRST survey. The contour levels are incremented by 10 per cent of the peak flux density unless stated otherwise. are as follows: J1225.0+2146, Peak flux density=23.05 mJy/beam, lowest contour is 10 per cent of the peak flux density. J1226.3+2418, Peak flux density=2.29 mJy/beam, lowest contour is 35 per cent of the peak. J1228.9+3114, Peak flux density=1.88 mJy/beam, lowest contour is 30 per cent of the peak. J1229.1+3040, Peak flux density=6.32 mJy/beam, lowest contour is 20 per cent of the peak. J1229.9+3712, Peak flux density=5.54 mJy/beam, lowest contour is 20 per cent of the peak. J1230.2+2326, Peak flux density=0.92 mJy/beam, lowest contour is 55 per cent of the peak with increments of 8 per cent.

**Figure 1. cont.** The contour levels are incremented by 10 per cent of the peak flux density unless stated otherwise. are as follows: J1230.6+3247, Peak flux density=0.59 mJy/beam, lowest contour is 60 per cent of the peak flux density with increments of 8 per cent. J1231.2+2538, Peak flux density=15.55 mJy/beam, lowest contour is 10 per cent of the peak. J1231.3+3724, Peak flux density=2.75 mJy/beam, lowest contour is 30 per cent of the peak. J1231.5+3236, Peak flux density=0.50 mJy/beam, lowest contour is 70 per cent of the peak with increments of 5 per cent. J1232.2+2814, Peak flux density=5.26 mJy/beam, lowest contour is 20 per cent of the peak. J1232.6+3157, Peak flux density=1.94 mJy/beam, lowest contour is 40 per cent of the peak.

**Figure 1. cont.** The contour levels are incremented by 10 per cent of the peak flux density unless stated otherwise. are as follows: J1234.3+2605, Peak flux density=1.73 mJy/beam, lowest contour is 40 per cent of the peak flux density. J1238.2+2613, Peak flux density=15.68 mJy/beam, lowest contour is 10 per cent of the peak. J1238.8+3559, Peak flux density=4.16 mJy/beam, lowest contour is 20 per cent of the peak. J1243.7+2830, Peak flux density=0.98 mJy/beam, lowest contour is 50 per cent of the peak with increments of 8 per cent. J1245.9+3320, Peak flux density=4.45 mJy/beam, lowest contour is 20 per cent of the peak. J1246.4+2516, Peak flux density=4.25 mJy/beam, lowest contour is 20 per cent of the peak.

**Figure 1.** cont. The contour levels are incremented by 10 per cent of the peak flux density unless stated otherwise. are as follows: J1248.2+2747, Peak flux density=4.34 mJy/beam, lowest contour is 20 per cent of the peak flux density. J1249.0+3615, Peak flux density=2.05 mJy/beam, lowest contour is 35 per cent of the peak. J1249.7+3408, Peak flux density=34.45 mJy/beam, lowest contour is 10 per cent of the peak. J1250.4+2941, Peak flux density=1.59 mJy/beam, lowest contour is 40 per cent of the peak. J1252.7+2207, Peak flux density=6.66 mJy/beam, lowest contour is 10 per cent of the peak. J1253.4+2703, Peak flux density=0.81 mJy/beam, lowest contour is 65 per cent of the peak with increments of 8 per cent.

**Figure 1.** cont. The contour levels are incremented by 10 per cent of the peak flux density unless stated otherwise. are as follows: J1253.6+2509, Peak flux density=0.55 mJy/beam, lowest contour is 70 per cent of the peak flux density with increments of 6 per cent. J1256.9+2509, Peak flux density=6.11 mJy/beam, lowest contour is 15 per cent of the peak.

**Figure 3.** Histogram of the  $K$ -band magnitudes of the 74 MHz USS sample (solid line) and the 151 MHz selected 6C\* sample (dashed line).

A Kolmogorov-Smirnov test shows that the two datasets are consistent with being drawn from the same underlying distribution, with the probability that they are drawn from different distributions significant at  $< 2\sigma$ . However, figure 3 does show that there are more bright near-infrared sources in the 74-MHz-selected USS sample. This is predominantly due to the fact that the 6C\* sample has an angular size limit of 15 arcsec, which may effectively filter out closer objects which are not excluded from the 74 MHz sample. Indeed, of those sources with  $K < 17$ , four of them have angular sizes  $> 15$  arcsec. Removing these sources from the distribution results in the distribution in the  $K$ -band magnitudes for the 74 MHz USS and 6C\* samples being completely indistinguishable, with the probability that they were drawn from the same underlying distribution  $> 99$  per cent ( $> 5\sigma$ ).

Given that the 6C\* sample has a median redshift of  $z \sim 1.9$  (Jarvis et al. 2001a), then we would expect that the USS sample discussed in this paper would have a similar redshift distribution, based on their  $K$ -band magnitudes. This is a much higher median redshift than unfiltered, complete surveys of similar flux-density limit, such as 7CRS where the median redshift is  $z \sim 1.1$  (Willott et al. 2002). Therefore, we are confident that the USS technique is still viable at 74 MHz, and as such we envisage that this sample will contain some of the highest redshift radio galaxies found to date.

## 6 SUMMARY

We have completed  $K$ -band imaging of a complete sample of 74 MHz USS sources selected from a region spanning  $165 \text{ deg}^2$ . This sample has been filtered using the steep-spectral index criterion to target the highest-redshift radio galaxies. We find that the distribution in the  $K$ -band magnitudes is similar that from a similar survey (6C\*) undertaken at the slightly higher frequency of 151 MHz.

However, the 74 MHz USS sample is relatively overabundant in brighter sources when compared with the 6C\* sample. This is predominantly due to the angular size cutoff used for the 6C\* sample which is not used for the 74 MHz USS sample here. Using this selection criteria on the 74 MHz USS sample would remove this bright near-infrared magnitude tail and the probability that the two samples are drawn

from the same underlying distribution is significant at  $> 99$  per cent.

The faint tail of the  $K$ -band magnitude distribution implies that we are still sensitive to the highest-redshift radio galaxies, with our faintest source having  $K > 20.7$  (3 arcsec aperture), suggesting a redshift of  $z > 5$  if we extrapolate the  $K - z$  relation for radio galaxies to  $z > 5$ .

The next stage in this project will be to gain spectroscopic redshifts of all of the sources in the sample, which will enable us to find some of the highest redshift radio galaxies and also constrain the evolution in the comoving space density of the radio source population.

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**Table 3.** Summary of the key observational results for the 74 MHz USS sample. The quoted RA and Dec are for the positions of the *K*-band IDs and all are J2000. † is a large source where the 74 MHz ID is associated with an extended lobe (Figure 2); for ‡ the quoted magnitude relates to the *K*-band ID at J1230.6+3247A; the *K*-band magnitudes marked with a \* are measured using a 5 arcsec diameter aperture, \*\* is measured in a 3 arcsec apertures, given due to the proximity of a *K*-band source to the ID. The quoted lower limit for J1229.1+3040 is the  $3\sigma$  limit in an 8 arcsec aperture. For # the quoted magnitudes are for the bright galaxy to the north east, the actual ID may not be visible in this image (see notes on this source).

| Source         | RA          | Dec         | 74 MHz flux density / Jy | $\alpha_{74}^{1400}$ | <i>K</i> mag (8 arcsec) |
|----------------|-------------|-------------|--------------------------|----------------------|-------------------------|
| J1225.0+2146   | 12 25 02.40 | +21 46 52.6 | 2.213                    | -1.25                | 19.54 ± 0.32            |
| J1226.3+2418   | 12 26 21.11 | +24 18 50.3 | 0.943                    | -1.36                | 16.608 ± 0.080          |
| J1228.9+3114#  | 12 28 59.56 | +31 15 01.1 | 0.608                    | -1.36                | 16.073 ± 0.069          |
| J1229.1+3040   | 12 29 07.75 | +30 40 41.2 | 0.356                    | -1.27                | > 19.7                  |
| J1229.9+3712†  | 12 30 02.98 | +37 12 46.1 | 0.635                    | -1.25                |                         |
| J1230.2+2326   | 12 30 14.31 | +23 26 14.5 | 0.968                    | -1.63                | 13.641 ± 0.019          |
| J1230.6+3247A‡ | 12 30 37.96 | +32 47 18.2 | 0.188                    | < -1.4               | 19.655 ± 0.502          |
| J1231.2+2538   | 12 31 15.00 | +25 38 28.0 | 1.064                    | -1.20                | 18.759 ± 0.225          |
| J1231.3+3724   | 12 31 20.71 | +37 24 14.7 | 0.477                    | -1.51                | 17.814 ± 0.177          |
| J1231.5+3236   | 12 31 32.78 | +32 36 28.1 | 0.311                    | -1.52                | 17.276 ± 0.119*         |
| J1232.2+2814   | 12 32 13.71 | +28 14 33.8 | 0.327                    | -1.36                | 19.363 ± 0.292*         |
| J1232.6+3157N  | 12 32 38.13 | +31 57 56.2 | 0.359                    | -1.35                | 17.151 ± 0.097          |
| J1232.6+3157S  | 12 32 38.25 | +31 57 50.7 | 0.359                    | -1.35                | 16.726 ± 0.078          |
| J1234.3+2605   | 12 34 23.95 | +26 05 49.7 | 0.402                    | -1.61                | 17.786 ± 0.176          |
| J1238.2+2613   | 12 38 12.42 | +26 13 44.0 | 0.728                    | -1.30                | 17.662 ± 0.162          |
| J1238.8+3559   | 12 38 49.44 | +35 59 21.4 | 0.634                    | -1.33                | 16.522± 0.087           |
| J1243.7+2830   | 12 43 42.80 | +28 30 55.5 | 0.712                    | -1.73                | 16.717 ± 0.096          |
| J1245.9+3320   | 12 45 54.30 | +33 20 33.0 | 1.140                    | -1.40                | 17.695 ± 0.151          |
| J1246.4+2516   | 12 46 24.55 | +25 16 32.4 | 0.347                    | -1.29                | 18.516 ± 0.223          |
| J1248.2+2747   | 12 48 13.62 | +27 47 22.8 | 0.624                    | -1.31                | 17.413 ± 0.143          |
| J1249.0+3615   | 12 49 01.46 | +36 15 34.4 | 0.440                    | -1.20                | 15.500 ± 0.047          |
| J1249.7+3408   | 12 49 43.43 | +34 08 08.5 | 1.383                    | -1.23                | 19.483 ± 0.340          |
| J1250.4+2941   | 12 50 28.45 | +29 41 44.2 | 0.395                    | -1.35                | 16.815 ± 0.092**        |
| J1252.7+2207   | 12 52 44.04 | +22 07 01.5 | 0.940                    | -1.22                | 17.447 ± 0.145          |
| J1253.4+2703   | 12 53 27.96 | +27 03 49.9 | 0.838                    | -1.30                | 16.511 ± 0.087          |
| J1253.6+2509   | 12 53 39.78 | +25 09 50.5 | 0.472                    | < -1.7               | 18.503 ± 0.322          |
| J1256.9+2811   | 12 56 58.15 | +28 11 09.7 | 0.524                    | -1.32                | 18.885 ± 0.257          |

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