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Optical observations of Ultra Steep Spectrum radio sources

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Abstract. In this paper we present follow-up optical observations of Ultra Steep Spectrum sources that were found by matching 150 MHz GMRT sources with either the 74 MHz VLSS or the 1400 MHz NVSS. These sources are possibly high-redshift radio galaxies but optical identification is required for clarification. The follow-up observations were conducted with the Liverpool Telescope; in all cases no sources are detected down to an R magnitude of ~23. By applying models and using the $K - z$ relation we are able to suggest that these sources are possibly at high redshift. We discuss how 2m class telescopes can help with the identification of HzRGs from large-scale, low-frequency surveys.

Keywords : radio continuum: galaxies – galaxies: high-redshift – galaxies: active

1. Introduction

Radio surveys play a crucial role in the study of active galactic nuclei (AGN) and they have several advantages over other methods. The emission tends to be much more powerful (than at other wavelengths). The most powerful sources at highest redshifts pin-point the most massive and luminous galaxies at such redshifts and crucially they are not affected by absorption by dust. In the local Universe, high-power radio galaxies are found in lower-density environments than low-luminosity radio galaxies. This means that powerful radio galaxies could serve as efficient probes of moderate redshift galaxy groups and poor clusters.

Radio sources can be detected out to high redshifts ($z > 5$). Empirically, it appears that the majority of high-redshift radio galaxies (HzRGs) tend to exhibit steeper radio spectra compared

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to lower redshift objects (De Breuck et al. 2000; Miley & De Breuck 2008). The origin of this is probably due to radiative ageing of the electron energy distribution, essentially the higher energy electrons radiate faster. Part of this relation may be due to a Malmquist bias; if a sample of objects is flux density limited then the observer will see an increase in the average luminosity with distance (this is due to the less luminous sources at large distances not being detected). It is likely that the higher gas densities in the galaxy environments at high redshifts play a role (Miley & De Breuck 2008). The larger densities constrict the development of radio bubbles from the AGN.

We know that the faint radio population is a mixture of several types of objects including faint AGN, normal spirals and ellipticals, and starburst galaxies. In general, very little is understood about the relative importance of the different classes of sources. Reasons for this include that the faint radio source samples are small, and the optical follow-up is incomplete (only 20% of sources have spectroscopic follow-up). With the spectroscopic redshifts a radio luminosity function (RLF) can be derived. The space density of sources increases with z up to $z = 2$ (Wall et al. 2005). Jarvis et al. (2001) found a constant comoving space density between $z \approx 2.5$ and $z \approx 4.5$. The main problem for establishing the high-z RLF is the small number of $z > 2$ radio galaxies. To determine this more accurately one needs to determine a method for detection of these radio galaxies. A very successful method for finding HzRGs is to construct a filtered survey and this can easily be achieved by picking sources which are Ultra Steep Spectrum (USS) sources (Miley & De Breuck 2008).

Having identified candidate HzRGs via their radio spectrum it is then necessary to identify the galaxies in the optical/infrared wavelengths, and subsequently determine the redshifts. Bright, nearby sources, are discarded by comparing positions with wide-field shallow surveys at optical and infrared wavebands. Next, follow-up observations in optical and infrared wavelengths are undertaken. In general the near-IR K-band is the most effective and up to 94% of sources have been detected down to $K = 22$ for sources with $S_{1.4GHz} < 50$ mJy (De Breuck et al. 2002). Once successful detections are made follow-up spectroscopic observations are made, allowing redshifts to be determined. HzRGs seem to have a relatively small scatter in a plot of K-band magnitude versus z, and they seem to be among the most luminous galaxies at high redshift (De Breuck et al. 2002). Apart from HzRGs there are a number of other sources that exhibit steep spectral indices. These include, but are not limited to, fossil radio galaxies, cluster halos and pulsars (Parma et al. 2007; Manchester et al. 2005).

In this paper we present follow-up observations of 3 USS sources determined by Giant Metrewave Radio Telescope (GMRT) observations at 150 MHz. The follow-up optical observations are conducted with the 2m Liverpool Telescope using RATCam with 3 bands (*RIG*).

2. USS Sources from the GMRT

George & Stevens (2008) presented a catalogue of 113 sources at 150 MHz with the GMRT with a flux density limit of 18.6 mJy (6σ). At 150 MHz the GMRT has a spatial resolution approaching

Table 1. USS sources taken from George & Stevens (2008). All sources have a spectral index $\alpha > 1.25$ in either the range 74–150 MHz or 150–1400 MHz.

Name	α_{74}^{150}	α_{150}^{1400}	Surveys / Detections
GMRT J033152.9−100843	2.5	0.8	VLSS $\surd$, GMRT $\surd$, NVSS $\surd$
GMRT J033216.0−083940	–	> 1.26	VLSS $\times$, GMRT $\surd$, NVSS $\times$
VLSS J033315.9−085119	> 2.5	–	VLSS $\surd$, GMRT $\times$, NVSS $\times$
GMRT J033318.7−085227	–	> 1.26	VLSS $\times$, GMRT $\surd$, NVSS $\times$
GMRT J033326.6−084205	–	> 1.42	VLSS $\times$, GMRT $\surd$, NVSS $\times$

$20''$, a positional accuracy of a point source better than $4''$, and for an observation of 8 hours a theoretical sensitivity of ~ 1 mJy beam^{-1}. The total area covered by the GMRT data in George & Stevens (2008) is ~ 3 deg^2. Table 1 lists the 5 candidate USS sources identified by this survey both by their presence and absence at 150 MHz. These sources were found by comparing the GMRT sources with both the National Radio Astronomy Observatory Very Large Array Sky Survey (NVSS) and the VLA Low-frequency Sky Survey (VLSS). The NVSS was made at 1.4 GHz with a spatial resolution of $45''$ and a limiting source brightness of about 2.5 mJy beam^{-1} (Condon et al. 1998). The VLSS was observed at 74 MHz with a spatial resolution of $80''$ and a typical source detection limit of 700 mJy (Helmboldt et al. 2008). After the GMRT sources are matched with the VLSS and the NVSS the spectral indices α ($S \propto \nu^{-\alpha}$) are determined. USS sources are determined as having either $\alpha_{74}^{150} > 1.25$ or $\alpha_{150}^{1400} > 1.25$. This is similar to the condition applied by De Breuck et al. (2000); however they determined the spectral index between 325 and 1400 MHz As discussed in the introduction, a steep radio spectral index does not automatically imply a high-redshift object and follow-up observations are necessary to confirm the nature of these sources.

For these objects we have investigated their nature using a variety of virtual observatory tools. None have been previously detected at optical wavelengths with the Digitized Sky Survey (DSS) or infrared wavelengths with either the Two Micron All Sky Survey (2MASS) or the Infrared Astronomical Satellite (IRAS). From the DSS maps no source can be seen down to the completeness level (R-band ≈ 20). From the 2MASS maps no source can be seen within twice the position errors of our GMRT observations. Based on this we determine that the source must be fainter than $J \sim 16$ and $H \sim 15.5$. Unfortunately, none of these sources are covered by UKIRT Infrared Deep Sky Survey (UKIDDS) or the Sloan Digital Sky Survey (SDSS).

Three of the sources from George & Stevens (2008) were chosen for follow-up observations. These sources are listed in Table 2 and the results of the virtual observatory search are given below:

1. GMRT J033152.9−100843 - the nearest source in the J-band (from 2MASS) is $41''$ away with a magnitude of 16.8.

2. VLSS J033315.9−085119 - the nearest source in the *J*-band (from 2MASS) is 47″ away with a magnitude of 15.7.

3. GMRT J033326.6−084205 - the nearest source in the *J*-band (from 2MASS) is 16″ away with a magnitude of 12.23; this may end up being a confusing source.

3. Optical observations

The Liverpool Telescope is a 2m unmanned fully robotic telescope at the Observatorio del Roque de Los Muchachos on the Canary island of La Palma (Steele et al. 2004). For our observations we chose to use the RATCam instrument which consists of a 2048 × 2048 pixel EEV CCD42-40, back-illuminated broadband chip with a pixel size of 13.5μm. These observations used filters: SDSS-*I* (693-867 nm), SDDS-*R* (556-689 nm) and SDSS-*G* (410-550 nm). Standard fields are based on the Landolt (1992) series of standards. They are spaced every few hours of RA and are observed in all bands. Basic instrumental reductions are applied to all RATCam images before the data are passed to users. This includes bias subtraction, trimming of the overscan regions and flat fielding. The data were obtained during photometric conditions with exposures of 400s (*I*), 150s (*R*), 50s (*G*). Full observational details can be found in Table 3. Zero-point calibration was provided by observations of Landolt stellar and star fields (Landolt 1992).

The observations took place between 17th and 29th August 2008 in photometric conditions. These observations are essentially a pilot for detecting HzRGs with the GMRT and 2m class robotic telescopes.

4. Results and discussion

Our Liverpool Telescope observations go much deeper than the DSS, theoretically reaching (for a 3σ point source) $G = 22.8$, $I = 23.3$, $R = 23.5$ with these observations approaching these estimates. The sensitivity of our observations are listed in Table 3. Fig. 1 shows *R*-band images of GMRT J033152.9−100843, VLSS J033315.9−085119 and GMRT J033326.6−084205. In all the observing bands no source can be seen at the location of the radio source. Deeper high-resolution multi-band optical observations are required to detect the optical counterparts of these sources and especially to resolve and characterise them.

We have presented *GRI*-band magnitude limits on sources with steep radio spectra. For these steep-spectrum sources the most commonly used (and most useful) band is the *K*-band. We will now relate our limits to these bands. Miley & De Breuck (2008) have presented an overview of the optical/infrared properties of HzRGS, showing the long-established correlation between the *K*-band magnitude and redshift – the $K - z$ relationship.

Bryant et al. (2009) discuss the $K - z$ correlation for a large sample of USS-selected radio galaxies using data from the 408-MHz Revised Molonglo Reference Catalogue and the 843-

Table 2. The USS radio sources followed up with the Liverpool Telescope. The source name, the object position, the radio flux densities at 74 MHz, 150 MHz and 1400 MHz and the source angular size (for GMRT sources at 150 MHz for VLSS at 74 MHz) are listed.

Source Name	RA (J2000.0)	DEC (J2000.0)	S_{1400} (mJy)	S_{150} (mJy)	S_{74} (mJy)	Size ($''$)
GMRT J033152.9−100843	03 31 52.97	−10 08 43.72	37.0	142.2	950	95.8
VLSS J033315.9−085119	03 33 15.89	−08 51 19.90	< 2.5	< 18.0	970	$\approx$130
GMRT J033326.6−084205	03 33 26.61	−08 42 05.86	< 2.5	56.4	< 100	39.1

Table 3. Results from Liverpool Telescope RATCam imaging. Given is the source name, observation date, the filter used, the exposure time and the observed limiting magnitude.

Source Name	Obs. Date	Filter	Exposure (secs)	Mag. Limit
GMRT J033152.9−100843	2008-08-29	*I*	400	23.0
	2008-08-29	*R*	150	23.2
	2008-08-29	*G*	50	22.6
VLSS J033315.9−085119	2008-08-17	*I*	400	22.5
	2008-08-17	*R*	150	22.5
	2008-08-17	*G*	50	22.0
GMRT J033326.6−084205	2008-08-17	*I*	400	22.1
	2008-08-17	*R*	150	23.0
	2008-08-17	*G*	50	22.0

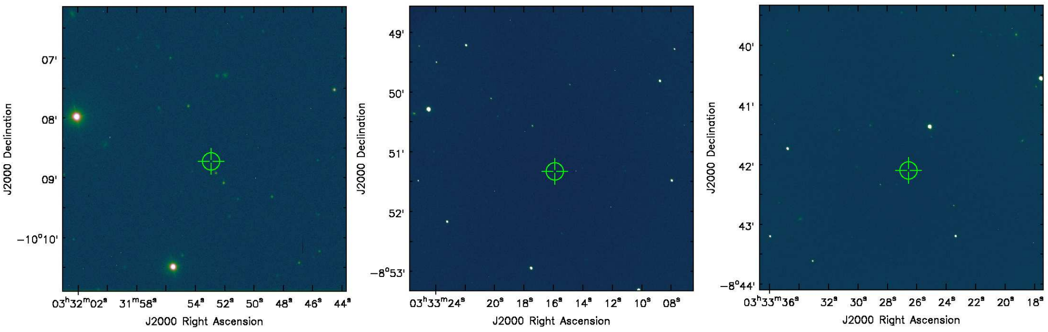

Figure 1. *I* band images of GMRT J033152.9−100843 (left), VLSS J033315.9−085119 (middle) and GMRT J033326.6−0842 (right) taken with the Liverpool Telescope). In all cases no sources are found at the position of the USS source. The field of view of RATCAM is 4.6′.

MHz Sydney University Molonglo Sky Survey (the MRCR-SUMSS sample), and the NVSS at 1400 MHz. Fitting the data, these authors find a correlation of the form

$$K = 17.75 + 3.64 \log_{10}(z) \tag{1}$$

where the K-band luminosity is measured with a 4″ aperture, and the relation applies for objects with $1 < z < 4$, and with a dispersion of around 0.7 mag on the relationship. Using spectral evolution models of Rocca-Volmerange et al. (2004), Bryant et al. (2009) find the properties of the galaxies consistent with being elliptical galaxies with masses in the range $10^{11} - 10^{12}\,\mathrm{M}_\odot$.

De Breuck et al. (2002) have discussed optical/near-IR imaging of 128 USS sources and noted that while 94% of the radio sources were identified down to a magnitude of $K = 22$, only around 50% were identified down a magnitude of $R = 24$. De Breuck et al. (2002) found that there was a large range in the $R-K$ colour of the USS sources, with some sources having values of $R-K$ in the range of 3–6, while for others, there are only limits with implied values of $R-K > 6$.

Using data from FIRST (Faint Images of the Radio Sky at 20 cm), El Bouchefry (2009a,b) has presented $R-K$ vs K and $I-K$ vs K colour-magnitude relationships for the sample of radio galaxies. The author notes that while there is a similar correlation between the $R-K$ and $I-K$ colours, there is also a larger scatter seen. Consequently, R and I band imaging is capable of detecting counterparts to USS sources, though the variation in the $R-K$ and $I-K$ colours means that the success rate is going to be variable. In this paper we have presented R-band limits of ~ 23 mag, and these will correspond to K-band limits in the general range of 17 – 20. By using Fig. 12 of Miley & De Breuck (2008) and assuming that the galaxy mass is $10^{11} M_\odot$ we are able to suggest that the sources are at $z > 0.5$.

5. Summary

USS sources were identified with the GMRT and we have conducted a virtual observatory search and follow-up observations. The observations of 3 USS sources with the Liverpool Telescope are ultimately inconclusive, with no detection in any of the 3 wavebands. Observations at infrared (in particular H and J bands) are required. We have presented R-band limits of ~ 23 mag, and these correspond to K-band limits in the general range of 17 – 20. By using correlations between K-band magnitude and redshift we can tentatively suggest that these are sources with $z > 0.5$.

The GMRT is well suited to complete a large sky survey of the low-frequency radio source population, going far deeper than has currently been explored with past surveys. If this is combined with archival observations and new targeted observations then this will enable the detection of previously undetected high-z objects amongst other sources. The ongoing TIFR GMRT Sky Survey (TGSS) - the radio continuum survey at 150 MHz using GMRT covering $\sim 30\,000\mathrm{deg}^2$ offers exciting prospects for the detection of many sources with interesting spectral indices. In the case of HzRG candidates once they have been identified via their spectral index it is crucial that deep optical/infrared follow-up is done. When there is no previous optical coverage we have shown that short 2m-class observations allow for preliminary exploration of sources. In the case of large-scale surveys this will be of great importance to filter the un-interesting sources.

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