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Synergy Between Radio and Optical Telescopes: Optical Followup of Extragalactic Radio Sources

C. H. Ishwara-Chandra
National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune University Campus, Pune 411 007, India.
e-mail: ishwar@ncra.tifr.res.in

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Abstract. Distance measurement is a must to characterize any source in the sky. In the radio band, it is rarely possible to get distance or redshift measurements. The optical band is the most used band to get distance estimate of sources, even for those originally discovered in other bands of the electromagnetic spectrum. However, the spectroscopic redshift measurements even for fairly bright radio sample is grossly incomplete, implying un-explored discovery space. Here we discuss the scope of optical follow up of radio sources, in particular the radio loud AGNs, from the present generation radio telescopes.

Key words. Galaxies: active—radio: general—galaxies: photometry—galaxies: spectroscopy.

1. Introduction

The most important and basic aspect for any source in the sky is to know its position and distance. While it is possible to get position to very high accuracy in the radio band, it is usually not possible to get distance (or redshift) measurements. Although there are a few spectral lines like HI and OH in the radio band, they are too weak in emission even in nearby objects, making it practically impossible to get redshifts. With the advent of ALMA (Brown *et al.* 2004), it is possible to observe several spectral lines in the mm band which could give redshifts, however, these will be galaxies that are mainly gas-rich and with massive star formation (Wang *et al.* 2013). The optical band continues to be the most used band to get distance estimate of extragalactic sources, even for those originally discovered in other bands of the electromagnetic spectrum. The major advantage in the optical band is that there are plenty of spectral lines. For active galaxies, many of the lines are strong enough to be detected in emission, even for very distant objects. Also, active galaxies are the most massive galaxies (Best *et al.* 1998; Rocca-Volmerange *et al.* 2004), which makes them the best probes of the early Universe. Therefore, optical followup is essential to characterize radio sources, in particular radio loud active galaxies. In this paper we will discuss optical follow up of radio sources, both from current generation telescopes and from upcoming major projects in both radio and optical bands. We will also touch upon the discovery space that is not yet exploited by the current generation of telescopes. The future large optical telescopes like TMT, are likely to fill the major gap that is left by the current generation of optical telescopes.

2. Nature of radio sources

Most of the radio sources in the sky are extragalactic, they are either starburst galaxies or active galaxies. The fraction of radio sources that belong to the Milky Way is negligibly small. At a radio frequency of 1 GHz, radio sources stronger than a few mJy are mostly active galaxies where the radio emission is powered by radio jets emanating from an Active Galactic Nucleus (AGN). Till about a decade ago, it was believed that sources fainter than a mJy are dominated by startbursts and contribution from active galaxies was ignored. However, recent deep radio, optical and X-ray surveys have suggested that even at sub-mJy levels, a substantial fraction of sources are radio weak active galaxies (Padovani *et al.* 2011). Here we review each class separately.

2.1 *AGN-dominated radio source population*

Most of the radio surveys until 1980s (like 3C, 4C, Parkes, MRC, etc.) consisted of strong radio sources with flux density of a few hundred mJy or more at 1 GHz. Almost all these sources were extragalactic radio loud AGNs, barring a few galactic supernova remnants and HII regions. If the ratio of the flux density at 5 GHz to 4400 Å is > 10, the active galaxy is considered to be radio loud (Kellermann *et al.* 1989), otherwise it is classified as radio quiet. The radio emission is mainly due to synchrotron and is not influenced by dust. Therefore radio sources are seen even from extremely large distances. For active galaxies that are radio loud, an added advantage is that their powerful radio emission is detectable from large distances and moreover they have prominent emission lines in the optical band making redshift determination easier as compared to equally distant normal galaxies. This makes the radio sources the favorite cosmological probes. We discuss this further in Section 3.

However, the fraction of radio sources with spectroscopic redshift measurement is minute, even for radio surveys stronger than a few tens of mJy. None of the radio samples, barring 3CRR which has just over 200 sources (Laing *et al.* 1983) and Robertson's 10 Jy catalogue with 160 sources (Robertson 1973) has complete redshift measured, but it took nearly four decades for this to be accomplished. The grossly incomplete spectroscopic redshift availability even for fairly bright radio samples, underscores the discovery space that remains to be explored. The farthest known radio galaxy is at redshift of 5.19 and has a flux density over 70 mJy at 1.4 GHz and much stronger at low radio frequencies due to its steep spectral index (van Breugel *et al.* 1999). This was discovered in 1999 and no other radio galaxy has been discovered beyond redshift of 5 till date, despite active programmes to search for HzRGs by various groups for nearly a decade since then (Miley & de Breuck 2008).

2.2 *Faint radio source population*

Conventionally, radio sources with flux density of ∼mJy or less were considered as faint radio source population and believed to be dominated by starbursts (e.g. Windhorst *et al.* 1985). The radio emission from starbursts is due to synchrotron emission from supernova remnants. These sources follow tight radio-FIR correlation, because the star formation rate is linked to FIR emission as well as number of supernovae.

However, with the advent of recent deep and ultra-deep surveys at optical and other bands, matching deep radio follow-up of these fields have been carried out at GHz frequencies with VLA (e.g. CDFS – Padovani *et al.* 2009; Lockman Hole – Ciliegi *et al.* 2003; Legacy Fields – Biggs and Ivision 2006) and ATCA (e.g. Akari – White *et al.* 2012). At GMRT, several of these legacy fields have been mapped with rms noise down to a few tens of microJy at 610 MHz (ElaisN1 – Garn *et al.* 2008; Lockman Hole – Ibar *et al.* 2009; VVDS-VLA – Bondi *et al.* 2007) and at 325 MHz (ElaisN1 – Sirothia *et al.* 2009; XMM-LSS – Sirothia *et al.* 2013). In Chandra Deep Field South (CDFS), radio sources down to ∼100 μJy at 1.4 GHz were found to be dominated by low luminosity AGNs and not startbursts, though the radio emission in these objects are predominantly from host galaxy and the AGN contribution is negligible. Below this limit, starbursts tend to dominate (Padovani *et al.* 2011). Therefore, characterization of faint radio surveys at optical and other bands like X-ray and IR, throw light on the faint AGN population, which was hitherto largely unknown.

3. New discovery space

As mentioned in Section 2.1, the fraction of radio sources with spectroscopic redshift available is very small, despite several decades of deep optical followup of radio source samples. For example, only 30% of the radio sources from VLA FIRST survey at 1.4 GHz (Becker *et al.* 1995) has been identified. While quasars could be seen up to redshift of 2, the galaxies are seen to much lower redshift (Ivezić *et al.* 2002). Similarly, the redshift coverage of 6dFGS is also much lower (Mauch & Sadler 2007). This leaves large scope for deeper and/or wider area optical followup, both for bright and faint radio source populations. Here we focus on the search for radio loud AGNs (bright source category) at very large redshifts ($z > 5$).

For several reasons, it is important to discover radio loud AGNs at high redshifts. Firstly, the radio luminosity function of HzRGs beyond redshift of 4 is poorly constrained (Cruz *et al.* 2007). It is important to understand whether there is a genuine dearth of HzRGs at $z > 4$ or the observed deficiency is a selection effect. Secondly, the host galaxies of HzRGs are among the most massive galaxies (Best *et al.* 1998), therefore, the formation and evolution of such galaxies at high-redshifts can be studied by picking them through the radio window. This will be complementary to the emerging population of Lyman Break Galaxy (LBG) population at high-redshifts, which are less massive by one to two orders of magnitude than AGN host galaxies (Schaerer *et al.* 2013). Also, LBGs do not possess AGNs. Thirdly, these objects are known to reside in dense environments, so are excellent tracers of protoclusters (Miley *et al.* 2006; Kuiper *et al.* 2012). Fourthly, since supermassive black holes are essential ingredients of radio-loud AGNs, the formation of supermassive black holes at such early epochs can also be probed using these objects. Therefore, radio-loud AGNs are excellent tool to study the cosmological evolution of galaxies. We will discuss some of the ongoing efforts to discover more HzRGs in Sections 3.1 and 3.2.

During the late 1970s, while searching for optical counterparts for radio sources a key observation was made, namely that the chance of finding optical counterparts are related to radio spectrum! In the sense that radio sources with normal radio spectrum ($\alpha \sim 0.75$; $S_\nu \propto \nu^{-\alpha}$) had much higher chance of showing optical counterparts as compared to sources with steep radio spectra ($\alpha > 1.3$) (e.g. Blumenthal & Miley 1979; Tielens *et al.* 1979; Gopal-Krishna & Steppe 1981) Such steep spectrum radio sources for which counterparts were not available at that time, were later shown to be high-redshift radio galaxies. This correlation of radio spectral index vs. redshift was exploited to discover a large number of high-redshift radio galaxies (HzRGs) successfully (Miley & de Breuck 2008; Ker *et al.* 2012). This technique remains the most successful in finding HzRGs. Till date, close to 50 HzRGs with $z > 3$ are known, with only one beyond redshift of 5.

In order to understand whether they represent typical FRII radio sources at high-redshifts, or the brightest among that category, we have compiled all the known HzRGs beyond the redshift of 3. The median flux density of all known HzRGs beyond redshift of 3 is 1.33 Jy at 150 MHz (Fig. 1). The present day radio telescopes can routinely detect sources down to more than two orders of magnitude than this value. We have computed the expected flux density at 150 MHz corresponding to the FRI/FRII break luminosity (assuming standard cosmological parameters) to understand the expected flux densities at 150 MHz for 'typical' radio galaxies at different redshifts. Thus, at a redshift of 3, the FRI/FRII break luminosity corresponds to a flux density of ~4 mJy at 150 MHz (assuming a spectral index of 1 for the K-correction). The corresponding values at redshifts of 4 and 5 are ~1.9 and ~1.1 mJy, respectively.

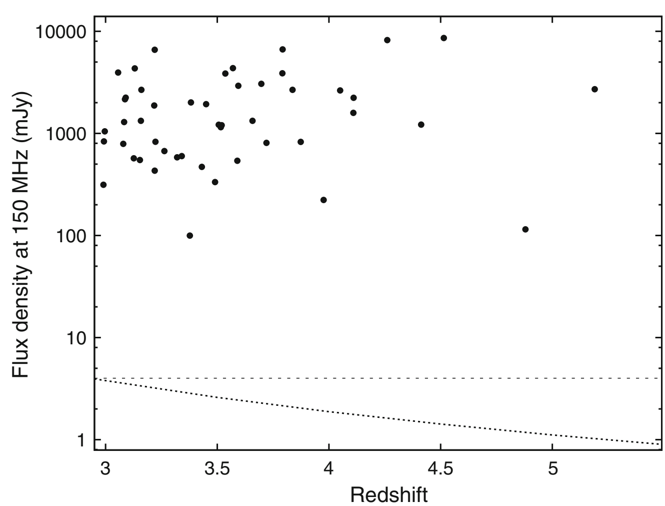

Figure 1. 150 MHz flux densities of the known HzRGs ($z > 3$) compiled using the available spectral index and flux density measurements. The dotted line at the bottom indicates the expected 150 MHz flux density corresponding to the rest-frame FRI/FRII break luminosity. The dashed horizontal line is the GMRT detection limit from the present 150 MHz observation. It is clear from this figure that a large number 'normal population' of FRIIs, that are 10 to 100 times less luminous than the known HzRGs are yet to be discovered.

Comparing this to the median flux density of the presently known HzRGs, it shows that the known HzRGs represent only the tip of the iceberg, i.e. they are the brightest objects in radio, at each redshift. There are, potentially, a large number of HzRGs yet to be discovered which are 10 to 100 times less radio luminous than the known HzRGs (see Fig. 1). Although it was believed in the 90s that there is a sharp drop in the radio luminosity function at high-redshift, subsequent to the discovery of several radio galaxies at $z > 4$, this supposition became suspect (Jarvis *et al.* 2001). From the radio luminosity function (RLF) of HzRGs, we could expect at least a 10-fold increase in space density of the radio sources beyond the redshift of 3 at radio luminosities 10 to 100 times lower than those of the known HzRGs (Waddington *et al.* 2001).

Systematic efforts are needed to detect this population of radio galaxies, which are not at the brightest end of the radio luminosity function. They are well within the reach of present day radio telescopes such as GMRT. As mentioned earlier, the most efficient method to find high-redshift radio galaxies is by exploiting the steep spectrum criteria. Recently, Ker *et al.* (2012) have thoroughly analysed the HzRG content in various radio surveys selected at low and high radio frequencies as well as the impact of different selection criteria in discovering HzRGs. It was conclusively shown that the samples selected at low radio frequencies such as 150 MHz, contains a much higher fraction of HzRGs as compared to sources selected at GHz frequencies. Thus, the large gap mentioned in Fig. 1 can be filled by searching for steep spectrum sources using deep radio observations with Giant Metrewave Radio Telescope (GMRT) at 150 MHz. GMRT consists of 30 fully steerable antennas, each of 45-meter diameter located 90 km from Pune, India. It operates at five frequency bands from 150 to 1450 MHz (Swarup *et al.* 1991). The system parameters and other details can be found at http://www.ncra.tifr.res.in/

3.1 *HzRG candidates from known deep fields*

We have started a programme using the GMRT to fill this gap, by observing several well-known deep fields at 150 MHz. The first one to be imaged was one of the field from the Leiden-Berkely Deep Survey (Fig. 2; Ishwara-Chandra *et al.* 2010). Two more fields from DEEP2 surveys were also observed and work is in progress to get reliable HzRG candidates from these fields.

The total number of sources in the LBDS field was ∼750. Using the already available data at 325, 610, 1400 and 4850 MHz, we have obtained spectral indices for all these sources (Ishwara-Chandra *et al.* 2010). Where there was no counterpart at higher frequencies, the spectral index limit was obtained by using 5-sigma value from VLA FIRST survey at 1.4 GHz. From this database, 157 sources with spectral index steeper than 1 were shortlisted and subjected to cross identification with the Sloan Digital Sky Survey (SDSS; Abazajian *et al.* 2009).

The positional accuracy at 150 MHz is not good enough to search for optical counterparts in SDSS. Therefore, we have cross-matched the above sample of 157 sources, having spectral index steeper than 1, with the VLA FIRST survey for which position accuracy is better than arcsecond (Becker *et al.* 1995). For the sources with a counterpart in the FIRST, we have used the FIRST position. In some cases where multiple components were seen in FIRST position of the core (or the centroid in case of a clear compact double lobe structure) was chosen. Among the 157 sources, eight

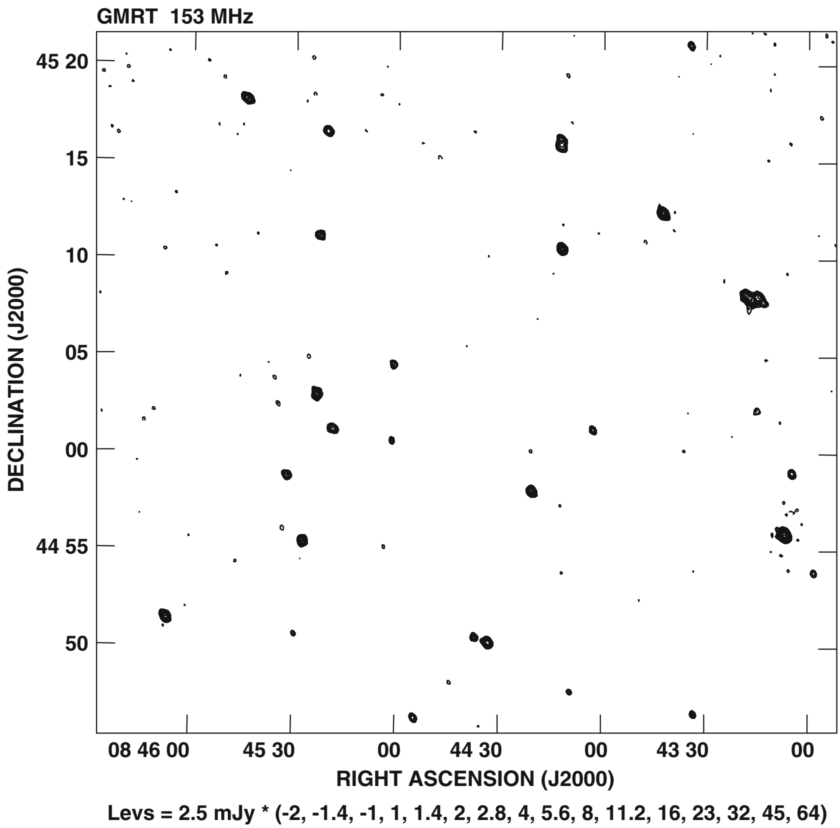

Figure 2. A region from the deep 150 MHz image of the LBDS field. The rms noise in the image is 0.7 mJy/beam at a resolution of $\sim 19 \times 15$ arcsec^2 with position angle of 27°.

sources did not have a counterpart in FIRST and hence the 150-MHz position was used to cross-match with SDSS.

There were 98 sources which had no optical counterpart in SDSS within 6-arcsec search radius and those are listed in Table 4 of Ishwara-Chandra *et al.* (2010). One of the steep spectrum source without SDSS counterpart (GMRT J084533+455835) is unresolved at 150 MHz, but shows a clear compact FR-II source of about 8-arcsec size in the VLA FIRST image. Using the 150-MHz flux density and the FR-I/FR-II break luminosity, we estimate the lower limit for this source at redshift of ~ 2.

We have also obtained data at 150 MHz for DEEP2 fields, centered at J2330+0000 and J0230+000, reaching an rms noise of 1.8 and 3.2 mJy respectively. In all, this 150 MHz catalogue has 1100 sources. Analysis to that mentioned above is underway. In this field too we found a faint unresolved source at 150 MHz, but showing an FRII morphology in FIRST, which suggests it to be at $z > 2$.

From the combined catalogue of LBDS and two of the DEEP2 fields, we expect about 250 steep spectrum radio sources lacking counterparts in the SDSS. These sources are potential candidates for HzRGs, and needs to be followed up with large optical telescopes.

3.2 *HzRG candidates from TIFR-GMRT sky survey*

TIFR-GMRT Sky Survey (TGSS) is an extragalactic radio continuum survey at 150 MHz, using the GMRT. It covers about 37,000 sq. degree of the sky north of declination of −55 degrees and reaches an rms noise of 5–7 mJy/beam at an angular resolution of about 20 arcsec. As in early 2013, about one steradian of images and catalogues consisting of ∼100,000 sources has been released for public use (refer http://tgss.ncra.tifr.res.in). When complete, the survey is expected to detect more than a million sources. Being a deep low-frequency wide area survey, it is well-suited for finding HzRGs using the steep radio spectrum criteria. We expect TGSS to provide about 10^5 radio sources with spectral index steeper than 1 and not having a counterpart in the SDSS, or equivalent optical surveys. Systematic efforts are needed to pursue these sources in optical and near-IR band, to discover HzRGs, mainly for the ones with redshift beyond 5.

4. Limitations of current optical telescopes for finding counterparts to radio sources

It is relatively straightforward to reach the above stage of listing candidate HzRGs, with optical counterparts undetected in existing optical surveys. However, proceeding from this stage onwards to spectroscopic redshift determination is expensive in telescope time. Since the number of such objects are, at best, a few per square degree, given small field-of-view of large optical telescopes, each object needs to be observed separately. The chance of such a source having redshift > 2 is ∼50%, (Pedani 2003), but the chance of it being at $z > 4$ is substantially lower. Each object needs to be imaged in K-band to get an estimate of redshift using $K - z$ Hubble diagram. Thereafter spectroscopic observation is needed to get accurate redshift. Therefore, given many candidates, the total time required to get spectroscopic redshift for all objects in the sample using current optical telescopes is large.

We believe, this limitation has deprived us of major discoveries, especially radio galaxies beyond redshift of 5. Systematic near IR and optical follow up of HzRG candidates like the one found in the GMRT samples will help to discover many HzRGs beyond redshift of 4. Only one HzRG (TN J0924-2201) is currently known at $z > 5$ (van Breugel *et al.* 1999). Finding more of them will be the prize catch for large optical telescopes.

5. Upcoming large optical telescopes

Fortunately, there are large optical telescopes on the horizon, which can meet the above challenge. For example, the Thirty-Meter Telescope (TMT), expected to be operational by 2020, will be the world's most advanced and capable ground-based optical, near-infrared and mid-infrared observatory (www.tmt.org). With 20 arcmin field-of-view and advanced adaptive optics capabilities, it will provide highly sensitive, diffraction-limited observations beyond 1 μm over most of the sky. The lone $z > 5$ HzRG, TN J0924-2201, which has a K band magnitude of 21.3 and required more than an hour of on-source time with Keck, would need less than a minute of observing time in IRIS with TMT (http://www.tmt.org/). For the science case discussed in this paper, TMT will not only will be able to provide spectroscopic redshift for the HzRG candidates, it will also be able to image neighboring area with IRMS to such a depth that it would be possible to check if the HzRG lies in a proto-cluster environment. We expect that the TMT will discover many more HzRGs beyond redshift of 5.

6. Concluding remarks

In this paper, we have covered science cases requiring deep optical and near-IR followup of radio sources, in particular high-redshift radio loud AGNs, from present generation radio telescopes. The spectroscopic redshift, essential to characterize the source, is available only to a very small fraction of bright radio sources. For example, even though several hundred quasars are known beyond redshift of 5, only one radio galaxy is discovered in this redshift range till date. This suggests requirement of more sensitive optical and near-IR observations of candidate HzRGs, which could help to discover more HzRGs beyond redshift of 5. The TMT, with its much improved sensitivity due to adaptive optics, will be able to fill this gap.

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