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Inferences from imaging extended radio sources in deep radio surveys

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Abstract. From the scales of the cosmic web to sub-kpc scales in 'radio-quiet' Seyfert galaxies, diffuse radio emission may form a component critical to our understanding of physics of extragalactic objects. Different aspects of the latter, ranging from the life-cycles of radio galaxies and the nature and cosmic evolution of sub-mJy radio population to dynamics of clusters of galaxies involve imaging diffuse radio emission. The observational difficulties imaging such diffuse emission which may typically be seen at low surface brightness levels makes sensitive radio surveys a necessity. Australia Telescope Low Brightness Survey(ATLBS) is such a survey. A radio survey at 1.4 GHz, it images 8.4 square degrees in the southern sky. Herein the results of studies of the radio sources in ATLBS survey are presented. We first demonstrate the importance of multi-resolution radio images and automated algorithms in accurately estimating the counts of radio sources in the submilliJansky flux density range. Using unique detection strategies to simultaneously mitigate effects of confusion and resolution bias, we have examined the counts of sources in the submilliJansky flux range. Using source counts as opposed to component counts, we find substantially lower counts below 1 mJy and conclude that the dominance of new populations is at lower flux densities than previously reported. Finally, we present a sample of radio sources chosen from the ATLBS survey regions and examine the links between the radio morphologies and their large scale optical environments using a novel method.

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1. Introduction

Extended, diffuse radio emission is important in many aspects of the studies of extragalactic radio sources. However, diffuse emission components associated with radio sources are difficult to capture, necessitating specific observational and imaging strategies. For population studies of radio sources, which give us important insights into cosmic evolution of radio sources and their attributes, including composition, life cycles and the influence of radio sources on cosmic structure formation process, sensitive surveys of large areas of the radio sky are needed. In this paper we present two studies of extended radio sources from ATLBS radio survey, which is a such a survey. In particular, we have focussed on 1) the source counts of radio sources, which give us information about the composition of the radio source populations (see Thorat et al. (2013a) for details) and 2) the optical environments of radio sources, which offer us clues about the radio sources and their interactions with their environments (see Thorat et al. (2013b) for details). In the next section we describe the observation and imaging of the radio and optical data of the ATLBS survey.

2. Observations and imaging

The Australia Telescope Low Brightness Survey (ATLBS) has been specifically designed to image diffuse radio emission in extended extragalactic radio sources at relatively high redshifts. To obtain the requisite surface brightness sensitivity with a radio interferometer, a synthesized aperture which is nearly complete is required. To this end, the radio data of ATLBS survey has been taken with excellent uv coverage. To ensure high dynamic range in the radio images, ATLBS survey images sky regions off galactic plane which are also devoid of strong radio sources. These regions are located in the southern sky in two adjacent fields, which we designate as A and B with their centers at RA:$00^h\ 35^m\ 00^s$, DEC:$-67^\circ\ 00'\ 00''$ and RA:$00^h\ 59^m\ 17^s$, DEC:$-67^\circ\ 00'\ 00''$. The radio observations were carried out in the 20 cm band (divided into two sub-bands with center frequencies of 1344 and 1432 MHz) in full polarization mode. The imaging of the radio data was carried out using techniques including multi-frequency deconvolution and cycles of self-calibration. Each of the two fields was covered with 19 separate pointings which were imaged separately and stitched together to create two final mosaic images. These mosaic images are free of artefacts, with a nearly uniform noise of 72 μJy beam^{-1} with a beam FWHM = $6''$, covering 8.42 square degrees. The mosaic images have excellent surface brightness sensitivity and provide a good representation of the diffuse, extended emission associated with radio sources.

The A and B fields of the ATLBS survey have also been observed in SDSS r' band, for the purpose of obtaining the information about the galaxies hosting radio sources as well as the optical environments of the radio sources. The optical observations were made with the CTIO 4 meter Blanco Telescope, Chile. The observations were carried out with the MOSAIC II imager, a mosaic of 8 CCDs, which allows imaging a sky region of size $37' \times 37'$ simultaneously. The imaging of the optical data was carried out using the MSCRED package of the IRAF software. The A and B regions were each covered with 14 optical images (in total 28 optical images). Each of these images were formed from stacking 5 dithers. The dithers were used to reject spurious sources such as satellite trails and cosmic rays. Using the Source Extractor software, galaxy catalogs for the ATLBS fields were constructed. The final optical images are complete down to 22.75 magnitude. In the next sections we describe the studies of extragalactic sources carried out using the radio and optical images.

3. Sub-mJy radio source counts

The radio source counts for the ATLBS radio survey were estimated using the radio and optical images. We have made use of novel techniques to generate a 'source list' (as opposed to a 'component' list which may count source components as separate sources). This source list was corrected for various biases to estimate the radio source counts.

Special care was taken to identify sources/component with low surface brightness by using low resolution (beam FWHM =50″) images (made with data from short baselines) for primary detection of sources. The source blending resultant from using low resolution images was addressed by using the high resolution images as well as optical images to identify separate sources. The use of low as well as high resolution images takes care of avoiding the resolution bias as well as blending issues. These strategies, in addition with the use of optical images to locate galaxy hosts of radio sources and visual inspection of radio sources with complex morphologies (instead of automated classification) ensures that source components are not identified as separate sources.

The source list thus composed was used to estimate the radio source counts down to ~ 0.4 mJy. A comparison of the ATLBS source counts with previous work shows that the ATLBS source counts are systematically lower and do not show the upturn in sub-mJy source counts down to the flux densities which we have probed. The lower source counts of the ATLBS survey may be attributed to the ATLBS source counts being derived from a source list as opposed to a component list (component counts may be as much as 50% higher than the true source counts at sub-mJy levels), as well as corrections for noise bias, which corrects for modifications of the true source counts because of sources shifting flux density bins due to the noise in the images. In addition, clustering effects may affect the source counts derived from small sky region coverage, which is a characteristic of many deep surveys. Our results highlight the need to use multi-resolution and multi-frequency data and to identify diffuse emission components reliably to estimate source counts correctly.

4. Optical galaxy environments of extended radio sources

In this section, we describe the study of optical environments of extended radio sources imaged in the ATLBS survey, which is made possible by the availability of optical images for the ATLBS survey fields. The motivation behind this study was to examine possible links between radio morphology and the optical environments of the radio source and to study the evolution in the optical environments with cosmic epoch. This study was restricted to those ATLBS radio sources which are extended (with a projected angular size more than $0.5'$) and thus are a sub-sample of the Extended Source Sample (ESS; presented in Saripalli et al. (2012)). The ATLBS ESS sample consists of 119 sources which have projected angular size greater than $0.5'$. We have applied a redshift cut at z= 1 to exclude sources with higher redshifts whose optical environments may not be well characterized due to the depth of the optical images. We have also excluded sources which do not fit constraints such as the availability of a host galaxy magnitude, the need for the radio sources not to be near the edge of the optical images etc. After excluding such sources, a sample of 43 extended sources was available for the study. This sample includes sources with different radio morphologies including FRI and FRII sources and Wide Angle Tailed (WAT) and Head-Tailed (HT) sources. It also includes 7 sources which are highly asymmetric in their radio morphology. For those sources for which there was no spectroscopic redshift available, we have estimated the source redshift from a magnitude-redshift relation derived from other sources in the ATLBS survey.

To estimate the optical environment of each radio source, we have created smoothed maps of optical galaxy distribution around each radio source. This was done by convolving the optical images with a matched filter (following the prescription as given in Postman et al. (1996)). The matched filter consists of a radial filter and a magnitude filter which follow the form of spatial and magnitude distributions of a cluster at the same redshift as the radio source. Thus the smoothed maps give the likelihood of a cluster at any given position, which we use to estimate the environmental richness of radio sources. Additionally, we have defined five parameters, which give estimates of the angular anisotropy of galaxy distribution around the radio source axis. This method is especially useful to quantify environmental asymmetry and is a new method.

The redshift evolution of the radio sources in the sample was studied using the parameters. Especially the environments of FRI/FRII sources were compared in two different redshift regimes, at high and low redshifts (corresponding to sources above and below redshift of 0.5). It was found that the environments of radio sources have similar richness in both redshift regimes, with no evidence of redshift evolution. WAT and HT sources, were found in the most dense environments. The latter result agrees with previous studies of WAT and HT sources, which place these sources in cluster or group environments. Examination of the anisotropy parameters for the asymmetric radio sources showed that higher density of galaxies was found on the shorter side of the radio source in six out of seven cases. This clearly shows the influence of environment on radio source morphology.

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