Discovery of Four Miscellaneous Radio Galaxies
From LoTSS DR1

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Abstract. Using the 144 MHz Low-Frequency Array (LOFAR) telescope, We undelook a search for Miscellaneous Radio Galaxies (MRGs) whose morphological structures are different from known structures. Reasons of study of these type sources due to their unique and peculiar morphology. Here, we report four MRGs from LOFAR Two Metre Sky Survey first data release (LoTSS DR1) at 144 MHz frequency. The MRS is identified manual visual search (MVS) from LoTSS DR1 data catalogue. We also check their radio morphology from other surveys like The NRAO VLA Sky Survey (NVSS) at 1400 MHz. The corresponding optical counterparts are also identified from Sloan Digital Sky Survey (SDSS), where available. We have estimated different physical parameters like spectral index, radio luminosity, radio power of these MRGs.

1. Introduction
The astrophysical jets are the extended and collimated outflows of the highly-ionized plasma which is powered by the central black hole. This narrow collimated jet usually connects the core to the extended components and the outer lobes of a radio source. Jets are the signatures of the beams carrying energy from the core to the outer lobes. It is widely believed that these sources are harbouring an active galactic nucleus (AGN) at their center. AGNs are characterized by a stellar or semi-stellar nucleus which exhibits evidence of variability at different wavelengths.
The emission of the jets from AGN consists all electromagnetic spectrum but for observation its dominated by the radio wave-band part. A typical double-lobed radio galaxy has two radio jets directed in the opposite direction from the central region. An optical galaxy, situated at the central region is known as optical host galaxy.

Based on the radio luminosity or brightness distribution radio galaxies are categorized into two major classes, one is Fanaroff-Riley class I (FR-I) and another is Fanaroff-Riley class II (FR-II) type [14]. FR-II sources have brighter hotspots at the outer edges of lobes compare to the central region. These sources are often referred to as edge brightened sources. FR-I objects have diffuse lobes of emission with no edge brightened structures and the central region are brighter than the outer edges of the lobes. FR-I sources are also known as edge darkened sources.

'Wide Angle Tail' (WAT) and 'Narrow Angle Tail' (NAT) are two sub-classes of radio galaxies at transition luminosity of FR-I and FR-II. WATs and NATs are together called Head-Tail (HT) radio galaxies [4, 5]. The opening angle between the jets of WATs and NATs are greater or less than 90° respectively. The main characteristic of these types of radio galaxies is that their jets are bent into a ‘V’, ‘C’ or ‘L’ like shape. These objects are usually found in the environment of rich clusters of galaxies [15]. They are supposed to be moving through the Intra-Cluster Medium (ICM) with sufficient velocities for the tails to bend by the action of the ram pressure [22]. The reason for the bending of the jet is the dynamic pressure which pushes back the jets. The reason for this pressure is the high velocity motion of the associated galaxy through the surrounding Intra Cluster Medium (ICM). A buoyancy force was also invoked to understand the bending of the jets. When the material density of the radio jets is less than the density of the surrounding medium, the buoyancy force comes into action. It pushes the lobes to the regions of ICM where the density of the jet is equal to that of the surrounding medium [18, 23].

There is some subclass of radio sources which exhibit some special morphology depending upon the orientation of the jet. For example, Winged’ (or X-shaped) [1, 2, 3] radio sources are a sub-class of extragalactic radio source that exhibits two, low-surface-brightness radio lobes (the ‘wings’) oriented at an angle to the active, or high-surface-brightness lobes, giving the radio galaxy an X-shaped or ‘Z’-symmetry [3] morphology as seen on radio maps.

The origin of such an exotic kind of sources is still unknown. There are some proposed models to explain the formation of such additional ‘wings’. Backflow of plasma from the active lobes is mentioned as the probable reason for the ‘wings’ [20]. The most accepted model considers a spin-flip of a supermassive black hole. In this spin-flip model, it is considered that when a merger happens, a relatively smaller super-massive black hole to be deposited to form a binary system with the larger black hole. The coalescence of super-massive black hole results a sudden reorientation of the spin axis of the larger hole due to the absorption of orbital angular momentum of the smaller hole and this change in spin orientation change the direction of the lobes [21].

There are a new group of double radio sources called HYbrid MOdorhology Radio Sources (HYMORS) [27]. The two lobes of these type of radio sources exhibit different FR morphological types. These HYMORS have FR-I morphology in one side of the AGN and FR-II morphology in another side. Hybrid radio morphology can be associated with galaxies, quasars and BL Lac objects. These radio sources extend from a few kiloparsecs to megaparsec dimensions. [27] first catalogued six good examples of such HYMORS. After inspecting 1700 sources from the FIRST survey [17] found three certain and two possible HYMORS. A total of 25 HYMORS are catalogued by [19]. [26] reported the discovery of a new HYMORS.

Throughout the paper, we adopt following cosmology parameters: $H_0 = 67.4$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.315$ and $\Omega_{vac} = 0.685$ [6]. The spectral index ($\alpha$) is defined by $S_\nu \propto \nu^\alpha$ where $S_\nu$ is the flux at frequency $\nu$ and $\alpha$ is the spectral index. All images are in the J2000 coordinate system.
2. Identifying new MRSs in LoTSS

2.1. The LoTSS first data release

The frequency coverage of LoTSS [24] survey is 120-168 MHz, conducted by high-band antennas (HBA) of LOFAR. Here we use first data release of LOFAR Two-metre Sky Survey (LoTSS DR1) [25]. The LoTSS DR1 spans (J2000.0 epoch) right ascension (RA) 10h45m to 15h30m and declination $45^\circ$00' to $57^\circ$00' covering 424 square degree with a median noise level across the mosaic of 0.071 mJy per beam and angular resolution of $6''$.

2.2. Search Method

First we select those sources which have angular size greater than $10''$ by our self made data reduction algorithm from LoTSS DR1 catalog. Manual visual search of shortlisted 18,500 sources. The radio core of the sources were searched in the SDSS optical band for counterparts. We search other wavelength data for each of the MRG we have identified. We cross-match respective data for MRG in TGSS at 150 MHz and in FIRST at 1400 MHz.

3. Result

In this paper, we report four MRGs from manual visual search of LoTSS DR1 data catalog. The morphological structures of these sources are different from X-sgape or ‘Winged’ radio galaxies or Heat-Tail (HT) radio galaxie or Double-Double Radio galaxies (DDRGs). They considered as MRGs because their jets orientaiions does not match any class of known classes. Here we discuss various properties of MRGs like nature, visualization difference and morphological structure. The morphology of GRGs also checked from other surveys like The NRAO VLA Sky Survey (NVSS) at 1400 MHz.

We have estimated the radio luminosity of each source. To calculate the radio luminosity ($L_{\text{rad}}$) we use the following relation adopted from [12].

$$ L_{\text{rad}} = 1.2 \times 10^{27} D_{\text{Mpc}}^2 S_0 \nu_0^{-\alpha} (1 + z)^{-(1+\alpha)} \times (\nu_u^{(1+\alpha)} - \nu_l^{(1+\alpha)}) (1 + \alpha)^{-1} \text{erg/s} \quad (1) $$

where $D_{\text{Mpc}}$ is luminosity distance to the source (Mpc), $S_0$ is the flux density (Jy) at a given frequency $\nu_0$ (Hz), $z$ is the red-shift of the radio galaxy, $\alpha$ is the spectral index and $\nu_u$ (Hz) and $\nu_l$ (Hz) are the upper and lower cut-off frequencies. In our calculation, we assume the upper and lower cutoff frequencies as 15 GHz and 100 MHz respectively.

The basic parameters of the MRG are mentioned in Table 1 and the color images extracted from the LoTSS DR1 catalog are shown in Figure 1. The MRGs are cataloged in Table 1 in the ascending order of Right Ascension (RA). Table 1 contains the following columns; column 1: Catalog Number, column 2: Name, column 3: RA (J2000.0), column 4: Declination (J2000.0), column 5: Position Reference, column 6: Red-shift ($z$), column 7: Angular size ($\theta$) in arc-second (Major Axis), column 8: Linear Size ($l$) in Mpc, column 9: flux density at 144 MHz in mJy.

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Figure 1. Grey stamp images of four MRGs J1204+4834, J1317+5614, J1323+5059 and J1428+4556 respectevly.
Table 1. Candidates of Miscellaneous Radio Galaxies

| Sl. No. | Name            | R.A. (J2000.0) | Decl. (J2000.0) | Ref. | z     | $F_{144}$ (mJy) | $F_{1400}$ (mJy) | $\alpha_{144}^{1400}$ | $L$ (erg/s) | $10^{42}$ | Other Cat |
|---------|-----------------|----------------|----------------|------|-------|----------------|----------------|----------------|-------------|----------|----------|
| 1       | J1204+4834      | 12 04 47.16    | +48 34 07.2    | SDSS | 0.0649 | 2956.3         | 118.1           | -1.42          | 3.44        | 2        |          |
| 2       | J1317+5614      | 13 17 29.13    | +56 14 43.1    | SDSS | 0.1076 | 368.8          | 12.7            | -1.47          | 1.33        | 1        |          |
| 3       | J1323+5059      | 13 23 05.08    | +50 59 11.5    | SDSS | -0.0001| 131.2          | 13.4            | -1.02          | —           | —        |          |
| 4       | J1428+4556      | 14 28 28.98    | +45 56 44.1    | SDSS | 0.4162 | 312.6          | 28.4            | -1.06          | 25.39       | 1, 4     |          |

References: (1)NVSS: [7]; (2)87GB: [9]; (3)SDSS: [16, 11]; (4)B3: [10];

$(F_{144})$, column 10: flux density in NVSS at 1400 MHz in mJy ($F_{1400}$), column 11: spectral index ($\alpha_{144}^{1400}$), column 12: Luminosity in erg/s ($L$), column 13: Other Catalog.

3.1. Notes on individual sources

In this section we provide notes on our interpretation of the radio morphologies for each of the four mrs.

1. **J1204+4834**: The LOFAR image of the radio source shows a annular shape with extension of radio lobes towards south, NW and east direction. These three extension gives a overall ‘triangular’ shape. The radio map indicates no radio emission at the central region. The optical counterpart of the radio source is SDSS J120447.35+483411.5 [16]. The source has a redshift of $0.064953 \pm 0.000190$ with magnitude 16.0 (g filter). The radio source may associated with the galaxy cluster WHL J120447.4+483412 [13], located at a distance 0.075 arcmin from the centre of the source.

2. **J1317+5614**: The primary lobes of the radio source is directed towards east-west direction. The radio plot of the source shows there is a pair of secondary lobes ejected from the central region. The secondary lobes are directed towards north to south direction. There is an extra and asymmetric lobe, that directed towards SW direction. Primarly the source looks like a ‘winged’ radio source, the presence of the asymmetric lobe gives the source a peculiar shape and hence a miscellaneous candidate. The optical galaxy SDSS J131729.13+561443.1 [16] is the optical counterpart of the source. The source has a redshift of $0.107570 \pm 0.000151$ with magnitude 16.2 in g filter.

3. **J1323+5059**: The LOFAR image shows that the source has a ‘triangular’ shape. The three lobes are quite symmetrically directed in the projected plane. The lobes are aligned towards west, NE and SE direction. It is seen that the edge of the SE lobe is bent towards south. There is a small extension of lobe is observed in the east direction, which is connected to the SE lobe. The optical counterpart of the source is SDSS J132305.08+505911.5 [16]. This has a blueshift with the value $-0.000103 \pm 0.000026$.

4. **J1428+4556**: The primary alignment of the radio source is NW to SE. The LOFAR image of the source indicates the source has three primary lobes. The lobe at the NW direction is a circular point like portion which is connected to the central core, containg the optical counterpart. The central region is more extended relative to the upper lobe with an extension towards west direction. SDSS J142826.95+455641.4 [16] is the optical counterpart of the radio source. The source has a spectroscopic redshift of $0.416175 \pm 0.000101$ with a magnitude value 21.4 in g filter.

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1. https://ned.ipac.caltech.edu/uri/NED::Refcode/2005SDSS4.C...0000:
2. https://ned.ipac.caltech.edu/uri/NED::Refcode/2004SDSS3.C...0000:
3. https://ned.ipac.caltech.edu/uri/NED::Refcode/2016SDSSD.C...0000:
4. https://ned.ipac.caltech.edu/uri/NED::Refcode/2016SDSSD.C...0000:
Figure 2. LOFAR image of the candidate miscellaneous radio galaxies (contours) overlaid on the DSS2 red image (grayscale). The contours are drawn from $\sim 3\sigma$ ($\sigma$ is local noise) to ensure a reliable structure. The contours are increased by factors of $\sqrt{2}$.

lobe arced and looked like a ‘C’-shaped radio source [5]. The orientation and extension of this three lobes makes the source as a candidate of miscellaneous radio source.
4. Discussion and Conclusion

Here we present peculiar structures radio sources as we found from LoTSS DR1 at 144 MHz. Based on their morphology each of the sources are unique and peculiar itself from known typical structure of radio galaxies like FR-I, FR-II type of double lobed radio galaxies, Head-Tail radio galaxies, winged radio sources, HYMORS and DDRG. After manual visual search of 18,500 sources from LoTSS DR1 catalog, we selected only four as MRG candidates. We also checked the crosscorrespond optical counterpart from SDSS and cross-checked their morphology of MRGs with NVSS.

The spectral index ($\alpha$) is a measure of the radiative flux density ($S$) on frequency ($\nu$). Observationally, it is noted that radio sources follow a gaussian distribution (dispersion $\pm0.11$) with the mean spectral index have the values in between $-0.63$ to $-0.89$ [28]. Later, the spectral index range for extended radio source is redened as $-1.8 < \alpha < -0.6$ [29, 30, 31, 32]. A relative deep study shows $-1.3 < \alpha < -0.5$ with concentration at the value $-0.8^5$. The $\alpha_{1400}$ for the MRGs are estimated in Table 1 and found that it varies between $-1.02$ and $-1.47$. This range implies that $\alpha$ of our MRG candidates falls well in the defined range of typical radio galaxies. We also estimated the radio luminosity $\sim (10^{41} - 10^{42})$ erg/s and this is also typical for a radio source.

The mechanism behind such unique structure of the radio sources should be different. For a radio source its morphology depends on the jet structure; actually the jet structure/morphology defines the overall structure/morphology of the respective radio source. The jets on the both side of the central AGN may be the same or sometimes they are different. There is also an another fact we should include is the jet-inter cluster medium (ICM) or jet-inter galactic medium (IGM) interaction. The jets interact with the ICM/IGM and thus change their shape, form and direction. Now the ICM/IGM on the opposite side of the AGN may not be the same always and hence each interaction results different scenrio. (Some jet interaction and other reasons with citations.) Any of these above described reasons may be the cause behind such miscellaneous radio morphology.

More in detail information for the sources are unavailable in literature. Though in some cases data at different frequencies are available, the resolution is too poor to resolve the fine miscellaneous structure. Further multi-frequency observations are needed to explain these morphologies and to understand mrs in general.

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