MRG: The Miscellaneous Radio Galaxies from the FIRST Survey

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Abstract. Miscellaneous Radio Galaxies (MRGs) are very rare kind of radio galaxies that exhibit unusual and different jet alignment and orientation from a typical radio galaxy. The peculiar and unique morphology of this type of radio source makes them a special case of study. In this paper, we report the identification of fifteen MRGs from VLA Faint Images of the Radio Sky at Twenty-Centimeters (VLA FIRST) Survey. The MRGs are identified manually by visual inspection of the FIRST database (December, 2017). The individual radio morphology of each source is cross-checked at different frequencies from other surveys like TIFR GMRT Sky Survey at 150 MHz and Westerbork Northern Sky Survey at 325 MHz. We also identify the associated optical counterparts from the Sloan Digital Sky Survey (SDSS), where available. The different physical parameters like spectral index and radio luminosity of these MRGs are also estimated. An overview on the origin of these unique sources are also drawn.
1. Introduction

Miscellaneous Radio Galaxies (MRGs) are those morphologically unique radio galaxies that could not be categorised as other known classes or sub-classes of radio galaxies based on the morphology of its jets. A typical double lobed radio galaxy consist of two oppositely directed radio jets from the central core, believed to be a active galactic nuclei (AGN). The jets are the extended and collimated outflows of the highly-ionized plasma which are powered by the central black hole. This narrowly collimated jets usually connect the core to the extended components and the outer lobes of a radio galaxy. These radio jets are the signature of the beams carrying energy from the core to the outer lobes. The orientation and alignment of the radio jets define the morphology of a source in a radio map.

Based on the morphology, radio sources can be classified into some classes and their subclasses. For example, ‘X’-shaped or ‘winged’ radio source [1, 2, 3] has a set of additional jets, which are aligned with a certain angle in addition to the two regular jets and gives an overall ‘X’-shape. In some cases, the set of secondary lobes comes from the edges of the primary lobes and gives a ‘Z’-symmetry [4, 3]. There is another class called head-tail radio sources [5, 6, 7], where two jets are bent in the same direction. This type of galaxies are classified into two categories as Wide Angle Tail (WAT) and Narrow Angle Tail galaxy (NAT). WATs have greater than 90° bending angle and NATs have less than 90° bending angle. Another class of radio galaxy is found where an additional pair of radio lobe is aligned along the direction of the primary jets and is known as double-double radio galaxy [8].

Along with the typical radio galaxy and such classes, some radio sources are found with unique morphology. Some literature is done before to study the uniqueness of such radio galaxies. Multiwavelength study of two unique radio galaxies Hercules A [9] and 3C 310 [10] have been done by [11]. Further investigation on the peculiar radio sources are done with M17 JVLA 35 [12] and IC 1531 [13]. The study of the peculiar source IC 1531 concludes that this could be a valuable target of observations for astronomers studying sources at the boundaries between radio galaxies and blazars [13]. Extragalactic radio source is an energetic physical process in the universe. Usually, such sources turn out to be radio galaxies, quasars or blazars, emitting strong radio waves. The radio galaxies may exhibit typical or unique morphology. The unique morphology could offer some important clues in the evolution of galaxies and groups of galaxies in general.

In this article, we present fifteen MRGs from a symmetric search of VLA FIRST survey data. The jet orientations of these type of sources are different from ‘winged’ radio sources or head-tail radio galaxy or double-double radio galaxy. Since the morphology of these sources does not match with any class of known radio sources, we treat them as Miscellaneous Radio Galaxies (MRGs). We discuss the morphological structure, nature, visualization differences and how they differ from typical sub-classes of a radio galaxy. The morphology of these MRGs are also checked with TIFR GMRT Sky Survey (TGSS) [14] at 150 MHz and the Westerbork Northern Sky Survey (WENSS) [15] at 325 MHz. In sec. 2 we discussed identification method of MRG from the FIRST survey. In sec. 3 we present the result of our work and discuss each source. Discussion and conclusions are presented in sec. 4.

Throughout the paper, we have used the following cosmology parameters: $H_0 = 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.315$ and $\Omega_{\text{vac}} = 0.685$ [16]. The spectral index ($\alpha$) is defined by $S_\nu \propto \nu^\alpha$ where $S_\nu$ is the flux density.

2. Identifying the MRGs

2.1. Observational Data

The study of detail morphology of a radio source requires better resolution data. At the frequency 1.4 GHz, the FIRST survey done in VLA B configuration covers a radio sky over 10,000 square degrees of the North and South Galactic caps. This survey has a typical rms ($\sigma$)
of 0.13 mJy and an angular resolution of 5″ [17]. The high-frequency sky survey like NRAO VLA Sky Survey (NVSS) at the same 1.4 GHz in VLA D configuration covers 82% of the celestial sphere with angular resolution 45″ and a rms of ∼ 0.45 mJy [18]. Other surveys like TGSS has a resolution 25″ and rms 3.5 mJy at 150 MHz [14], and at 625 MHz WENSS has the resolution and rms as 54″ and ∼ 18 mJy (5 sigma_{rms}) respectively [15]. The better resolution and high sensitivity of the FIRST survey [19] allow us the possibility of studying the morphologies of a large number of moderately weak radio galaxies. Hence, we use the FIRST database for our study to detect MRG candidates.

2.2. Search Method
First, the sources having an angular size greater than 10″ are selected. This value was chosen because we preferred to search for relatively extended sources. Radio maps of 95,243 sources extracted from the FIRST survey inspected visually and the candidates are selected. The position of the optical counterpart is taken as the position of the radio sources in Table 1. The optical counterpart of the MRG is identified from Sloan Digital Sky Survey (SDSS) catalog [20]. For those sources whose optical counterpart are not found, the center of the radio map is taken as the position coordinate. For position coordinate, we use an eye estimated (EE) position. The morphology of the identified MRG are cross-checked at 150 MHz and 325 MHz from TGSS and WENSS survey respectively.

3. Result
A total of fifteen sources that appears to be MRG candidates in the FIRST database is reported. We have studied the morphology of each source from the FIRST image. We also have collected the respective red-shift of the sources from their corresponding optical counterparts, where available. The flux density of each source are measured from the TGSS at 150 MHz and the respective spectral index between 1400 MHz and 150 MHz (\(\alpha_{1400}^{150}\)) are calculated.

Figure 1. Color stamp images of the fifteen FIRST MRG candidates.
Table 1. Candidates of Miscellaneous Radio Source

| Sl. No. | Name          | R.A.       | Decl.     | Ref.  | z    | θ       | l       | \( F_{1400} \) (mJy) | \( F_{150} \) (mJy) | \( \alpha^{1400}_{150} \) | \( L \) (erg/s) | \( (\times 10^{41}) \) | Oth. Cat. |
|--------|---------------|------------|-----------|-------|------|---------|---------|---------------------|---------------------|---------------------|-------------|-----------------|----------|
| 1      | J0041+0958    | 00 41 31.26 | +09 58 31.8 | EE    | —    | 68      | 56.6    | —                   | —                   | —                   | —           | 1, 2             | 1        |
| 2      | J0707+4327    | 07 07 11.67 | +43 27 09.6 | EE    | —    | 35      | 22.5    | 85.5                | —                   | —                   | —           | 1, 2             | 1        |
| 3      | J0803+1500    | 08 03 37.68 | +15 00 52.4 | SDSS  | 0.142| 112     | 85.2    | 663.1               | —                   | —                   | —           | 1, 2             | 1        |
| 4      | J0858-1107    | 08 58 26.92 | -11 07 17.3 | 2MASX | —    | 75      | 101.9   | 448.0               | —                   | —                   | —           | 1, 2             | 1        |
| 5      | J0901-6237    | 09 01 12.56 | -62 37 18.5 | SDSS  | —    | 42      | 184.6   | 771.8               | —                   | —                   | —           | 1               | 2        |
| 6      | J1043-0553    | 10 43 18.94 | -05 53 52.5 | WISE  | 0.549| 52      | 826.8   | 344.7               | 1427.1              | —                   | —           | 1               | 1        |
| 7      | J1119+3750    | 11 19 46.88 | +37 50 51.3 | EE    | 0.485| 31      | 27.1    | 184.2               | —                   | —                   | —           | 1, 2             | 1        |
| 8      | J1125+2005    | 11 25 54.82 | +20 05 03.4 | EE    | —    | 50      | 111.0   | 806.8               | —                   | —                   | —           | 1               | 2        |
| 9      | J1218-1813    | 12 18 04.89 | -18 13 53.6 | SDSS  | 0.140| 83      | 126.8   | 1056.2              | —                   | —                   | —           | 1               | 2        |
| 10     | J1440+1125    | 14 40 20.78 | +11 25 07.1 | SDSS  | 0.150| 58      | 125.5   | 776.7               | —                   | —                   | —           | 1, 2             | 1        |
| 11     | J1452+0212    | 14 52 24.11 | +02 12 01.2 | EE    | —    | 63      | 201.8   | 970.9               | —                   | —                   | —           | 1               | 2        |
| 12     | J1454+2210    | 14 54 17.40 | +22 10 55.8 | SDSS  | —    | 85      | 96.2    | 495.1               | —                   | —                   | —           | 1               | 2        |
| 13     | J1530-0703    | 15 30 58.88 | -07 03 32.4 | 2MASX | —    | 102     | 110.3   | 598.8               | —                   | —                   | —           | 1               | 2        |
| 14     | J1636+4505    | 16 36 49.99 | +45 05 11.3 | EE    | —    | 38      | 75.0    | 561.4               | —                   | —                   | —           | 1               | 2        |
| 15     | J2155-0846    | 21 55 26.16 | -08 46 48.4 | SDSS  | 0.150| 58      | 125.5   | 776.7               | —                   | —                   | —           | 1               | 2        |

References: (1) NVSS: [18]; (2) VLSS: [21, 22]; (3) TXS: [23]; (4) PMN: [24]; (5) 87GB: [25]; (6) B3: [26]; (7) 6C: [27, 28, 29, 30, 31, 32]; PKS: [33]; SDSS: [20, 34]; 2MASS: [35]; 2MASX: [35]; WISE: [36, 37]

We have estimated the radio luminosity of each source. To calculate the radio luminosity \( (L_{rad}) \) we use the following relation adopted from [38].

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

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 FIRST 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 1400 MHz in mJy (\( F_{1400} \)), column 10: flux density in TGSS at 150 MHz in mJy (\( F_{150} \)), column 11: spectral index \( \alpha_{1400}^{150} \), column 12: Luminosity in erg/s (\( L \)), column 13: Other Catalog.

3.1. Notes on individual sources

1. **J0041+0958**: The source looks like a double-double radio galaxy (DDRG). A typical DDRG has two pairs of lobes with a common center in a straight line [8]. The radio source, J0041+0958 has four proper lobes. The inner and outer pairs of lobes are not in a straight line. The outer side of the south lobe is in a straight line with the inner two lobes, while the outer lobe in the north side has deviated from the straight line towards the west direction. This deviation of the north side outer lobe makes this source a different one from a DDRG. The radio source shows such type of morphology may be due to the presence of a massive component like galaxy cluster or massive black hole at the east direction, as the north side of the outer lobe bends towards the west direction. There is no optical counterpart found for this source. No data found in TGSS at 150 MHz and WENSS at 325 MHz for this particular source.

2. **J0707+4327**: The radio source has three arms that are symmetrically aligned in three directions, gives the whole source a ‘spinner’ like shape. The three lobes are directed towards the west, north, and south-east (SE) direction. The angles between the lobes of west and north,....
north and SE, SE and west are 110, 125 and 125 degrees respectively. We see that at 1.4 GHz frequency, out of the three lobes the SE and north lobes have nearly equal flux with the values 5.7 mJy and 5.8 mJy respectively, while the west lobe has a flux density 6.9 mJy. The central core has a flux density of 4.0 mJy at 1.4 GHz. We check this source at different frequencies for such a ‘spinner’ like structure. It looks like a point source both in TGSS and WENSS due to poor resolution. Re-orientation of any of the jets or restarting of jet ejection in a different direction may be the reason behind such peculiar structure.

3. **J0803+1050**: The jets of the radio source has two kinds of bent structure on the two sides of the central region. The upper jet of the source is a perfect resemble with ‘S’, but the shape of the lower half is a sharp ‘U’. There is also a small ‘wing’ towards the east direction from the lower ‘U’-shaped portion. The optical counterpart of the radio source is SDSS J080337.68+105042.4 [20]. With a red-shift value of 0.142356 [39] and an angular size of ~ 112′′ the radio source has a linear size of 0.38 Mpc. The galaxy cluster WHL J080337.7+105042 [40] is very near (angular separation ~ 0.1′′) to the source and may be associated with the source. The radio source has a moderate luminosity of $3.44 \times 10^{41}$ erg/s. No counterpart is found in WENSS at 325 MHz for this source. The TGSS database at 150 MHz has not enough resolution to observe such kind of morphology as seen in FIRST.

4. **J0858–0107**: The morphology of this radio source is quite interesting, the upper portion of the jet has a ‘C’-shaped structure, while the tail towards the north is further extended. The upper lobe is much brighter than the lower part. A galaxy cluster WHL J085829.2–010704 [40] is present inside the radio map of the upper lobe. In NVSS catalog this source is mentioned as NVSS J085829-010720 [18], though lack of resolution of NVSS miss such miscellaneous morphology. Both in NVSS at 1.4 GHz and TGSS at 150 MHz, it seems to be a point-like source. There is no counterpart found in WENSS for this source.

5. **J0901+6237**: The primary jets are directed from NW to SE when the wings are in SW to NE direction. Interestingly the NW primary jet bends towards the south and meets with the SW wing as seen from the color image. The source is found to be a point-like source in WENSS and TGSS.

6. **J1043–0553**: The radio source J1043-0554 is a quasar LQAC 160-005 001 [41]. The source may be a head-tail source with a ‘U’-shaped extension towards NE. A radio-loud region is spotted at the SE edge of the source. The radio flux of this radio hot-spot is measured as 243.9 mJy at 1.4 GHz, while the total radio flux of this source is 334.4 mJy. So the SE upper edge has a 73% of the total radio flux, the radio source has. This is also cataloged as UVQS J104318.95-055352.5 [42] and as TXS 1040–056 with flux 658.0 mJy at 365 MHz [23]. No data is found in WENSS at 325 MHz. The source detected as a point-like source in TGSS (150GHz).

7. **J1119+3750**: The radio source looks like the letter ‘t’. The primary jet is arched to form a bent structure while a pair of nearly equal and oppositely directed secondary lobes come out from both sides of the primary jet in the north and south direction respectively. Three optical galaxies are found inside this radio source. We checked that the optical galaxy SDSS J111946.94+375038.6 [20] with red-shift 0.486700 [43] lies in the north secondary lobe, when SDSS J111947.40+375058.9 [20] with red-shift 0.486218 ± 0.000261 1 is seen inside the south secondary lobe. The primary jet which has formed the tail of the shape ‘t’ contains the optical galaxy SDSS J111946.26+375055.8 [20]. As the above three optical galaxies have not coincided

1 http://www.sdss.org/dr5/products/catalogs/index.html
Figure 2. FIRST image of the candidate miscellaneous radio sources (contours) overlaid on the DSS2 red image (grayscale). The contours are drawn from $\sim 3\sigma$ ($\geq 3.0 \times 10^{-4}$ Jy) to ensure a reliable structure. The contours are increased by factors of $\sqrt{2}$.

with the center, we take EE position of the center of the radio source as a position coordinate. The north and south secondary lobes have the respective flux values 2.7 mJy and 1.7 mJy at 1.4 GHz. The search for the morphology of this radio source in TGSS and WENSS, shows a point-like radio source instead of such miscellaneous structure.
Figure 3. FIRST image of the candidate miscellaneous radio sources (contours) overlaid on the DSS2 red image (grayscale). The contours are drawn from $\sim 3\sigma \geq 3.0 \times 10^{-4}$ Jy to ensure a reliable structure. The contours are increased by factors of $\sqrt{2}$.

8. **J1125+2005**: The source J1125+2005 seems to be a radio cloud. It may be an H I region. The radio source has a crab nebula [44] like structure. Four distinct radio hot-spots are visible in color image. The multi-wavelength deep-field study is needed to understand this source. No optical counterpart has been found for this radio source. The radio source has an angular size of $\sim 50''$. The previous identification of the source is NVSS J112554+200505 [18].

9. **J1218+1813**: The radio source gives a cloud-like emission. A triangular like morphology is noticed from the radio map. The optical counterpart of this radio source is SDSS J121804.89+181353.6 [20]. The galaxy 2MASS J12180539+1813466 [35] and 2MASS J12180420+1813455 [35] both are inside the radio region and may also be the candidate as the optical core. Like J1125+2005, this radio source may also be an H I region source. The TGSS data for this source shows a quite similar kind of radio cloud-like structure. No counterpart is found in WENSS.

10. **J1440+1125**: The outward jets of the radio source are along the north-east and west direction. The north-east jet is compact when the west jet has a diffused structure. A bent structure like ‘C’ is seen in the central part. The edges are more luminous compared to the

\[^2\] http://images.nrao.edu/393
arched region of the central ‘C’ shaped region. The galaxy cluster WHL J144020.8+112507 [40] is located at an angular distance 0.04 arcmin from the optical counterpart, SDSS J144020.78+112507.1 [20] of this radio source. The galaxy cluster may be associated with this radio source. TGSS data is available and the source seems to be a point-like source. No database is found in WENSS at 325 MHz.

11. J1452+0212: The source consists of three radio lobes. The three lobes are nearly equispaced in our projected plane. In an anti-clockwise direction, the angle between the west, south and north lobes are 110, 105 and 145 degrees respectively. The radio source has a total radio flux 201.8 mJy at 1.4 GHz. The measured individual flux values for the south, north and west lobes are 76.3 mJy, 61.6 mJy and 64.1 mJy respectively. The optical galaxy SDSS J145222.58+021203.4 [20] may be the optical counterpart for this radio source, which is inside the radio map of the western lobe. The three-lobe structure is not resolved in any other survey.

12. J1453+2210: This is a special bent radio source. Considering the structure of the jets from the center, the jets initially are steep and directed towards the south direction and thereafter both the jets go flat towards the west. The west side jet shows again extended towards the south and thus the whole jet structure makes the source very peculiar. An extended structure is found in TGSS, but lack of resolution gives an unresolved structure. No counterpart is found in WENSS.

13. J1530–0703: The primary alignment of the radio jets is directed towards the east to west direction. Both of the radio jets have a compact core towards a common center and diffuse edges in the opposite direction. Interestingly the east lobe is further extended towards north to south and makes the overall morphology of the radio source a special one. In the NVSS catalog, the two lobes are cataloged as two different sources, the east one is known as NVSS J153100–070343 [18] when the west one is named as NVSS J153056-070333 [18]. Two distinguishable lobes are seen in TGSS but the resolved structure is not found. There is no data found in WENSS.

14. J1636+4505: The radio jet has a clear hot-spot at the center with two jets directed towards north and south. The south radio jet bent in a ‘C’-shape while the north jet is a typical straight jet. This jet structure makes the source a peculiar one. The south and north jet has the flux value 16.0 mJy and 11.3 mJy respectively. The relatively loud central region has a flux 47.5 mJy at 1.4 GHz. From the other frequency observations like WENSS at 325 MHz and TGSS at 150 MHz, the source looks like a point source. No optical counterpart is found for this radio source.

15. J2155+0846: The radio source has a bent upper jet with a straight lower jet that yields the whole source a mirror image of question mark (‘?’) like shape. The upper bent jet is more luminous than the lower one. The radio source is associated with a galaxy cluster, RM J215526.2+084648.4 [45]. A point-like source is detected in TGSS when there is no data found in WENSS.

4. Discussion and Conclusion
Extragalactic radio sources represent some of the most unusual, extreme and energetic physical processes in the universe. The main objective of this study is to find extragalactic radio sources which are unique in morphology. Morphology of these type of sources is somehow different from

https://phys.org/news/2018-10-peculiar-radio-source-ic.html
the known class and subclass of radio sources like head-tail radio source, winged radio source, HYMORS and DDRG. Due to the unusual morphology, these sources are treated as MRGs. After a systematic search of 95,243 sources from the FIRST catalog, a sample of fifteen sources are selected as the MRG candidates. We have found the corresponding optical counterpart from SDSS and also cross-matched the morphology of the selected fifteen candidates with TGSS and WISE. As the resolution of the above mentioned two surveys is poorer than FIRST, the MRGs are unresolved and look like point source for most of the cases.

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 $\pm 0.11$) with the mean spectral index have the values in between $-0.63$ to $-0.89$ [46]. Later, the spectral index range for extended radio source is redefined as $-1.8 < \alpha < -0.6$ [47, 48, 49, 50]. A relative deep study shows $-1.3 < \alpha < -0.5$ with concentration at the value $-0.84$. The $\alpha_{1500}$ for the MRGs are estimated in Table 1 and found that it varies between $-0.60$ and $-0.95$. 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 $\sim (10^{41} - 10^{43})$ erg/s and this is also typical for a radio source.

The mechanism behind such special structures of the radio sources should be different and not clear to us. We can conclude the following points as the probable reasons behind such miscellaneous morphology:

— For a radio source, its morphology depends on the orientation and structure of the jet. The jets, ejected from the central core (AGN) need not to be symmetric. There may be differences in shape, size, luminosity and sometimes in the composition also.

— The environment on the both side of the central core (AGN) within which the jets propagate, may be different. The discrepancy on the two side affect the propagation of the jets in two different ways.

— Through the process of the propagation the jets encounters with a set/number of interaction with the Inter Galactic Medium (IGM) and (/or) Inter Cluster Medium (ICM). The interacting ICM or IGM are not happened to be same and so the ineractions, for each of the jet.

— Along with these we may also include the black flow of plasma, the re-orientation of jets, the spin-flip, the merging of two binary sources, the presence of massive cluster – as the probable reasons.

Any of these above-listeded reasons or any combination of the reasons may be the cause behind such unusual 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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