Cosmic Evolution of Nearby Radio Active Galactic Nuclei

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Abstract. The exact formation mechanism of massive galaxy in the universe still become an open question in modern astrophysics. Radio emission from active galactic nucleus (AGN) is known to be suppressing stellar growth in the most massive galaxies, thus becoming significant ingredient in modeling galaxy formation process. Radio luminosity function across cosmic redshifts ($z$) is an important tool to constrain the co-evolutionary models of radio AGN and its host galaxy. Therefore, we aim to calculate radio luminosity function at 1.4 GHz frequency for radio AGN in the range of $0 \leq z \leq 1$. In this work, the radio data was taken from deep VLA observation of Stripe 82 field at angular resolution of 1.8" and 52 $\mu$Jy sensitivity. On the other hand, the optical/near-infrared data was taken from Dark Energy Survey DR1 observation in $g$, $r$, $i$, $z$, $Y$ bands with co-added catalog limiting magnitude of $i = 23.44$. We estimated the photometric redshift (photo-$z$) of each sources by using combined two machine learning algorithms: neural networks and boosted regression trees. We successfully performed accurate photo-$z$ measurement with average bias ($\delta$) = $-3.5 \times 10^{-3}$, scatter ($\sigma$) = 0.15 and outlier fraction ($f(3\sigma)$) = 0.06. By using $1/V_{\text{max}}$ method, we calculated the luminosity function, then constrained their evolution with pure density evolution (PDE) or pure luminosity evolution (PLE) model. At median $z = \{0.31, 0.59, 0.88, 1.10\}$, we found the power-law index of PDE is $\alpha_D = \{1.29, 1.43, 1.73, 0.94\}$ while for PLE is $\alpha_L = \{2.28, 2.59, 3.19, 1.63\}$. Our result is consistent with previous studies and gives better constraint to radio AGN luminosity and density evolution power-law indexes due to larger number of sources (6900) and wider covered sky fraction (92 deg$^2$).

1. Introduction
The exact mechanism of massive galaxy formation still leaves big question in modern astrophysics. Radio emission from active galactic nucleus (AGN) is known to be suppressing star formation in the most massive galaxies, thus becoming significant ingredient in modeling galaxy formation process. By now, radio jets feedback from AGN has become a primary prescription in semi-analytic models and is able to well-reproduce the observed properties [1]. The produced outflows heats the massive galaxy halo gas and quenches its star formation, suppress the growth and thus set certain limit on the assembled mass.

Past studies have shown that there are different evolutionary schemes of radio AGN which is consistent with "cosmic downsizing" phenomena. This means faint radio-luminosity objects evolve more weakly compared to the luminous ones. The number density peak located at higher...
redshift for higher radio luminosity. Radio luminosity as a function of cosmic redshifts ($z$) is very useful to constrain the co-evolution of radio AGN and its host galaxy models [1]. In this work, we will determine the radio luminosity function at 1.4 GHz frequency for radio AGN at $0.1 \leq z \leq 1.3$.

2. Data

2.1. Radio catalog

The radio sources were obtained from high resolution 1.4 GHz Very Large Array survey that was conducted by [2]. This observation has an angular resolution of $1.8''$ and $52\mu$Jy beam$^{-1}$ sensitivity over $92\text{ deg}^2$ in Stripe 82 field. There are 17969 isolated radio sources from this catalog that can be used.

2.2. Optical photometry data

We use the data from Dark Energy Survey Data Release 1 [3] to search the optical counterparts of our radio sources. DES is an optical/near-infrared imaging survey conducted by the Dark Energy Camera, attached on the 4-m Blanco telescope of CTIO in Chile. Current data release covers $5000\text{ deg}^2$ in five broad photometric bands of the southern Galactic cap. The catalog depth for median co-added images with 1.95'' aperture diameter at SNR = 10 is $\{g, r, i, z, Y\} = \{24.33, 24.08, 23.44, 22.69, 21.44\}$ mag. We focus on searching galaxy candidates in Stripe 82 field by using this SQL query:

```
SELECT * 
FROM dr1_main main 
JOIN dr1_magnitude mag ON main.COADD_OBJECT_ID = mag.COADD_OBJECT_ID 
WHERE 
(main.ra BETWEEN 315 AND 360 OR main.ra BETWEEN 0 AND 45) 
AND main.dec BETWEEN -14 AND 5 
AND main.imaflags_iso_z = 0 
AND main.imaflags_iso_i = 0 
AND main.imaflags_iso_r = 0 
AND main.imaflags_iso_g = 0 
AND main.flags_z < 4 
AND main.flags_i < 4 
AND main.flags_r < 4 
AND main.flags_g < 4 
AND main.spread_model_i BETWEEN -0.05 AND 0.05 
AND ( 
(CASE WHEN spread_model_i + 1. * spreaderr_model_i > 0.003 THEN 1 ELSE 0 END) + 
(CASE WHEN spread_model_i + 3. * spreaderr_model_i > 0.005 THEN 1 ELSE 0 END) + 
(CASE WHEN spread_model_i - 1. * spreaderr_model_i > 0.003 THEN 1 ELSE 0 END) 
) > 2
```

The obtained objects in this catalog is named as main optical catalog.

2.3. Spectroscopic catalog

We assemble public spectroscopic catalogs which will be used later to determine photometric redshifts (photo-$z$) of objects in our main optical catalog. For all of these catalogs, we limit our search to include only objects within $0.01 < z < 9$, not stars or artifacts, and redshift error cut
of $\sigma_z < 0.005 (1 + z)$. Additional criteria were applied for each survey to ensure high quality spec-$z$ measurements and summarized in Table 1. Then, we match our main sample with this compiled spectroscopic catalogs by using 1" matching radius.

### 3. Photo-$z$ Determination
We utilize ANNz2 [12], a new version of neural network photo-$z$ code ANNz [13]. This version incorporates additional machine learning algorithms more than Artificial Neural Networks (ANNs), such as k-Nearest Neighbors (KNN) and Boosted Decision Trees (BDTs). These methods are contained the TMVA package [14]. To train the software, we run ANNs 120 times and randomly varied the parameters such as training cycles count, number of nodes in each layer, the type of activation function, the utility of Bayesian regulator that minimizes the over-fitting risk, the type of variable transformation performed before training (e.g. PCA transformation and normalization), the number of convergence test, and initial random seed. The performance test is then measured through optimization scheme which leads to a photo-$z$ value. The full set of solutions is then used to make the probability distribution function (PDF) of photo-$z$. For the first step, each solution is folded with its error, that was derived before with KNN error calculation as in [15]. Then, the ensemble solution is constructed after the optimization is done and weighting scheme applied. This will allows us to calculate both the intrinsic uncertainties on the input parameters and the errors on the method itself. The aforementioned methodology is called "randomized regression". In addition, a useful feature in ANNz2 is the weighting scheme for training data [16]. This technique were applied to make the training data distributions becoming more representative of the test data.

### 4. Result and Analysis
In this section, we will discuss methods of determining the LF from our data, then show the fitting procedure, and present the LFs for our radio AGN. Derived parameters will give us constraint on how radio AGN and its host galaxy are connected, which is valuable ingredient in modeling this type of system.

#### 4.1. Estimating the luminosity function
First, the assumption that radio sources are dominant in radiating synchrotron emission in its radio spectrum and can be described with power-law $S_\nu \propto \nu^\alpha$ is made. Here $\alpha$ is the spectral index and $S_\nu$ is monochromatic flux density at specific frequency $\nu$. In cosmological context, standard radio $K$-correction is defined as $K(z) = (1 + z)^{-(1+\alpha)}$. Hence, the rest-frame radio

| Survey       | Criteria                                         | Reference                              |
|--------------|--------------------------------------------------|----------------------------------------|
| SDSS/BOSS   | $z$Warning = 0                                   | Abolfathi et al. (2018)                |
| DEEP2       | qFlag = 4 ($> 99.5\%$ confidence)                | Davis et al. (2003), Newman et al. (2013) |
| VIPERS      | qFlag = 3–4 ($> 95\%$ confidence)                | Garili et al. (2014)                   |
| VVDS        | qFlag = 3–4 ($> 95\%$ confidence)                | Le Fèvre et al. (2013)                |
| GAMA        | qFlag = $\geq 4$ (highly confident)              | Liske et al. (2015)                    |
| WiggleZ     | qFlag = $\geq 4$ (highly confident)              | Drinkwater et al. (2010)              |
| UDSz        | qFlag = $\geq 4$ ($> 95\%$ confidence)           | Bradshaw et al. (2013), McLure et al. (2013) |
luminosity $L_{\nu_1}$ at specific frequency $\nu_1$ can be derived from the observed redshift $z$, luminosity distance $D_L$, and flux density $S_{\nu_2}$ at frequency $\nu_2$ as

$$L_{\nu_1} = \frac{4\pi D_L^2(z)}{(1+z)^{1+\alpha}} \left(\frac{\nu_1}{\nu_2}\right)^\alpha S_{\nu_2}$$

(1)

The choice of specific frequency at 1.4 GHz is simply to make it easier to compare our results with other literature. We assumed a standard $\alpha = -0.7$ if the power law index measurement is not available. This assumption is valid median value for radio galaxies as explained by [17].

To determine the LF (density of sources as a function of luminosity) at certain range of redshift bins, we utilized the $V_{\text{max}}$ method [18]. Basic principle of this method is to calculate the maximum observable volume of each object of interest, constrained with certain selection criteria. One advantage of this method is because it is independent from LF’s shape so that selection and sample biases can be minimized. The LF $\Phi(L, z)$ describes the number of object as a function co-moving volume and luminosity and is expressed as

$$\Phi(L, z) = \frac{1}{\Delta \log L} \sum_{i=1}^{N} \frac{1}{V_{\text{max},i}}$$

(2)

where $\Delta \log$ is luminosity bin width, $V_{\text{max}}$ is the maximum observable co-moving volume of i-th source, and the summation is calculated over each source i in certain luminosity and redshift bin. To consider various effects and biases (e.g. non-uniform noise in the radio observation and luminosity limited sample) which results in incompleteness, the maximum observable volume $V_{\text{max}}$ is calculated in general form equation which is

$$V_{\text{max},i} = \sum_{z=z_{\text{min}}}^{z_{\text{max}}} [V(z+\Delta z) - V(z)]$$

(3)

where the summation begins at a certain redshift bin and adds together co-moving volume of spherical shells $V(z+\Delta z) - V(z)$ in small redshift intervals $\Delta z = 0.01$ until redshift bin end.

Following [19], the root-mean-square errors of LF in each luminosity and redshift bin is estimated by weighting the number of objects which contribute to the summation and expressed as

$$\sigma_{\Phi} = \frac{1}{\Delta \log L} \left[ \sum_{i=1}^{N} \frac{1}{V_{\text{max},i}} \right]^{\frac{1}{2}}$$

(4)

However, if there are less than ten objects in a luminosity bin, we take the error as lower and upper 84% confidence interval. These intervals compatible with Gaussian 1$\sigma$ errors so that $\sigma_{\Phi} = \Phi \times \sigma_N/N$. Here $\sigma_N$ is Poissonian asymmetrical error.

4.2. Radio luminosity function evolution

Radio AGN population evolution can be parameterized by luminosity and density evolution of its local luminosity function as

$$\Phi(L, z) = (1+z)^{\alpha_D} \times \Phi_0 \left[ \frac{L}{L^*} \right]^{\alpha_L}$$

(5)

where $\alpha_L$ is luminosity evolution parameter and $\alpha_D$ is density evolution parameters, respectively, $L$ is luminosity, $\Phi(L, z)$ is the number density at redshift $z$, and $\Phi_0$ is the local luminosity function. Analytical equation for nearby radio AGN LF that we use is two power-laws model, taken from [20] as

$$\Phi_0(L) = \frac{\Phi^*}{(L^*/L)^{\alpha} + (L^*/L)^{\beta}}$$

(6)
By definition, the parameters are the scaling constant \( \Phi^* = \frac{1}{10^{5.5}} \text{Mpc}^{-3} \text{dex}^{-1} \) (normalized to the base of \( d \log L \)), the turning point \( L^* = 10^{24.59} \text{W Hz}^{-1} \), and the slopes of faint and bright end \( \beta = -0.49 \) and \( \alpha = -1.27 \), respectively. We take the radio AGN population luminosity function as determined by [20] and model its evolution by using Equation 6.

**Figure 1.** Best-fit for pure luminosity and pure density evolutions for each redshift bin. Our data is shown as blue dots with error bars while data from [1] and [17] are shown as magenta and green dots with error bars, respectively.

In Figure 1 we show the best-fit parameter of pure luminosity (PLE; \( \alpha_D = 0 \)) and pure density (PDE; \( \alpha_L = 0 \)) evolutions for each bins, which can be thought as cases of evolution in extreme regime. The calculated parameters are also tabulated in Table 2. The median pure density evolution and pure luminosity power-law indexes for all considered redshift bins are \( \langle \alpha_L \rangle = 2.37 \pm 0.14 \) and \( \langle \alpha_D \rangle = 1.27 \pm 0.05 \), respectively. Our result is consistent with [1] finding.
### Table 2. The value of best-fit LF evolution parameters for each redshift bin.

| Median redshift (z) | PDE ($\alpha_D$) | PLE ($\alpha_L$) |
|---------------------|------------------|------------------|
| 0.32                | 1.15 ± 0.22      | 2.17 ± 0.44      |
| 0.59                | 1.39 ± 0.05      | 2.56 ± 0.15      |
| 0.88                | 1.73 ± 0.04      | 3.09 ± 0.12      |
| 1.10                | 0.94 ± 0.03      | 1.58 ± 0.07      |

5. Summary and Conclusion

We derived the 1.4 GHz radio luminosity function of 6900 radio AGN at $0.1 \leq z \leq 1.3$ in this work. The radio data were taken from deep VLA observation of Stripe 82 field while the optical/near-infrared data were taken from Dark Energy Survey DR1. By using $1/V_{\text{max}}$ method, we calculated the luminosity function, then put stringent constraints on the the evolution of the population via PLE or PDE model. At median $z = \{0.31, 0.59, 0.88, 1.10\}$, we found the power-law index of PDE is $\alpha_D = \{1.15, 1.39, 1.73, 0.94\}$ while for PLE is $\alpha_L = \{2.17, 2.56, 3.09, 1.58\}$. Our result is consistent with previous studies and gives better constraint to radio AGN luminosity and density evolution power-law indexes due to larger number of sources (6900) and wider covered sky fraction (92 deg$^2$). Furthermore, we found that high-luminosity radio AGN follow the double power-law model, similar to the low-luminosity AGN, indicating that there isn’t any difference of evolution between high- and low-luminosity AGN population.

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