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On the morphological dichotomies observed in the powerful radio galaxies

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Abstract. We study environment and host galaxy properties of powerful radio galaxies with different radio morphologies from compact sources to very extended double lobed radio galaxies and with different optical spectra classified as high excitation (HERG; quasar-mode) and low excitation (LERG; jet-mode) radio galaxies. We use a complete sample of morphologically classified radio sources from [1] and perform three different analyses: i) we compare compact radio sources with the extended sources from the same class of excitation. ii) we compare HERGs with the LERGs using a combined sample of compact and extended sources. iii) we investigate the origin of different morphologies observed in the very extended powerful radio galaxies, historically classified as Fanaroff-Riley (FR) radio galaxies of type I and type II by comparing a sample of FRIs with the FRIIs from the same excitation class. We discuss the results and what causes the differences in each comparison. The role of host galaxy and the central super massive black hole, and the galaxy interactions are all investigated.

1. Introduction

Radio galaxies are identified by their luminous radio emission or large-scale radio jets and lobes, which are originated from parsec-scale region near the super massive black hole (SMBH) and expand up to hundreds or thousands of kpc away. They live and evolve in a wide range of galaxies and environments and present various radio morphologies and the optical spectra. Sources with very extended radio emission are classified into type I (FRI) and type II (FRII) [2]. The peak of radio emission is located near the core in FRIs while the region of highest surface brightness are located at the edge of the radio lobes in FRIIs. In contrast, there is a class of objects with compact radio emission and no extended component classified as FR0 [3]. There is a lot of discussions about whether these three classes of radio sources have the same origin or they are fundamentally different objects [4–9].

The optical spectra of radio galaxies are also different [10]. While most of the radio galaxies have weak emission lines (LERG) in their spectrum, some of them have highly excited emission lines (HERG). Previous works claimed that the black hole feeding mechanism is responsible for these differences in the optical spectrum of radio galaxies [11].

The origin of morphological differences is not well understood up to the present time. The previous studies investigated both intrinsic and extrinsic parameters to explain the observed differences. In this study, we explore the SMBH, host galaxy and environment of radio galaxies to explain the radio morphological dichotomies using a complete sample of FR classified radio galaxies; crucially, we match the samples in their excitation state in order to isolate the dependencies on radio morphology only. We also consider the HERG/LERG dichotomy using morphologically matched samples. Throughout the paper we assumed a ΛCDM cosmology with the following parameters: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 100h$ km s^{-1} Mpc^{-1} where $h = 0.70$.

2. Sample selection

The radio source sample and the parent galaxy sample are taken from [11]. They have cross-matched SDSS DR7 with the 1.4 GHz radio surveys of NVSS and FIRST [1]. We applied the redshift cut of $0.03 < z < 0.1$ due to the spectroscopic and photometric limitations of optical data and a 40 mJy flux density cut to achieve sufficient signal-to-noise for morphological classification. Radio sources have been classified according to their radio structures into FRI, FRII and compact. The detail of FR classification is presented in [1,12] who have constructed a sample of > 1000 morphologically classified radio galaxies. FRI and FRII sources constitute an extended source radio sample to be compared with the compact objects. We keep extended objects with angular sizes above $20''$ due to the uncertainty in morphological classification at smaller sizes. The method we adopted for HERG/LERG classification is presented in [11]. Therefore, we have constructed six samples of FRI/FRII/compact HERG and FRI/FRII/compact LERG available for this study. The numbers of HERG sources are dramatically lower than the LERG sources. Figure 1 shows the redshift distribution of FRI, FRII and compact sub-samples.

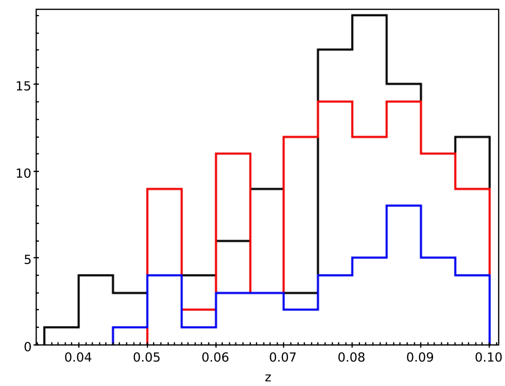

Figure 1. The redshift distribution of compact (black), FRI (red) and FRII (blue) radio galaxies used in this study.

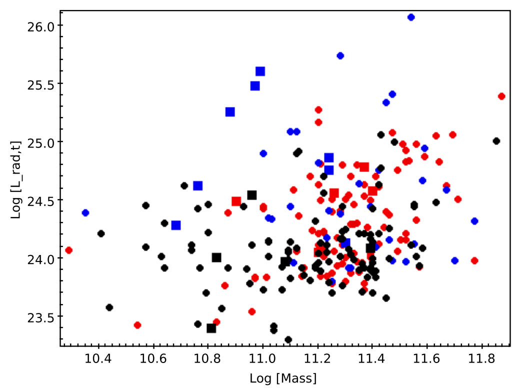

Figure 2. The total radio luminosity versus stellar mass for compact (black), FRI (red) and FRII (blue) radio galaxies separated into HERG (square) and LERG (circle).

3. The comparisons and results

In order to understand the origin of observed differences in the radio morphology and optical spectrum of the radio galaxies, we perform three comparisons. We first explore FRI/FRII dichotomy using a sample of FRI LERGs and FRII LERGs. The HERG sources have been excluded from the comparison so that the results are not biased by the HERG/LERG differences. We also remove mass and radio luminosity biases by comparing a two dimensional matched sample of FRI and FRII in stellar mass-total radio luminosity plane (figure 2). The matching strategy is randomly choosing FRI/FRII pairs in the 2D plane, which satisfy the matching error in radio luminosity Δ log[L] = $\pm$ 0.2 and mass Δ log[M] = $\pm$ 0.1. For the final results of comparisons, we average over 1000 iterations of the random matching. The significance of differences are confirmed by the Kolmogorov-Smirnov (KS) test.

Two types of parameters have been explored in this work. The first group of parameters represents the host galaxy properties of the radio sources include *black hole mass* estimated using the velocity dispersion of the galaxy and the relation between the velocity dispersion and the black hole mass given in [13]; the host galaxy *optical size*, which is parameterized by the radius containing 50 percent of the galaxy light in the r-band (R_{50}); *surface mass density* defined by the relation: $\mu_{50} = 0.5\ M_{\star}/\ (\pi R_{50}{}^2)$; *concentration* of the galaxies that distinguishes the bulge-dominated systems from disk-dominated systems and is defined by the ratio of the radius containing 90 % of the galaxy light to the radius containing 50 % of the galaxy light ($C=R_{90}/R_{50}$), note that galaxies with high concentration ($C>2.6$) are typically bulge-dominated systems whereas galaxies with $C < 2.6$ are mostly disk-dominated systems; host galaxy *colour* (g–r); *age* of the host galaxy which is estimated by the strength of the $4000\AA$ break of the galaxy optical spectrum, the young stellar populations have small $4000\AA$ break while old galaxies have large $4000\AA$ break; and the *[OIII] luminosity.*

The second group of parameters represents the environmental properties that are introduced by Sabater *et al* [14] and include the galaxy number *density* of the environment, which is parameterized by the distance to the 10th nearest neighbour of the target galaxy; *tidal interaction* estimated by the sum of tidal forces of the neighbour galaxies with respect to the internal binding forces of the target galaxy; *richness* of the galaxy group or cluster that the target galaxy belongs and is defined by the number of member galaxies in the group or the cluster. The last two environmental parameters are defined by the combination of density and tidal interaction according to the principal component analysis (PCA) in order to remove the correlation between these two parameters including *PCA1* and *PCA2.* PCA1 traces the overall interaction level and environmental density of a galaxy and PCA2 traces one-on-one interactions in which a lower value shows galaxies that are relatively isolated for their overall environment.

After constructing the matched sample, we compare the black hole, host galaxy and environment of FRIs with the FRIIs. The results show that FRIs reside in smaller galaxies with higher concentration, higher mass surface density and higher black hole to stellar mass than FRIIs. Therefore, the host galaxy in FRIs shows less disk-like structure. Comparing the environment of FRIs with FRIIs shows that FRIs lie in richer local environment having higher density, PCA1 and richness. The dense environment, particularly in galaxy groups and clusters, is the place in which highly concentrated galaxies like giant ellipticals have been formed so the result from the comparison of FRI/FRII host galaxies and environments are consistent. We can conclude that radio jets in FRI sources are probably disturbed by the dense surrounding environment and form a core dominated radio lobe with a diffused radio tail, while jets in FRIIs freely expand and form a giant radio lobe far from the center.

We apply the method that we described above to the compact LERGs and compare them with a sample of extended objects constructed by combining FRI LERGs and FRII LERGs. For this analysis, the 2D matching plane is of the stellar mass-core radio luminosity. The results show that the only significant difference is the black hole mass. Surprisingly, compact sources have lower black hole mass compared to the extended sources. So galaxies with higher black hole mass seem to be more likely to form large scale radio jets. Since there is no other significant differences, we conclude that the compact sources could be fundamentally different objects from the extended sources.

The previous comparisons were limited to the LERGs objects to remove the HERG/LERG bias. In the third analysis, we construct a 2D matched sample of HERG sources with the LERGs in stellar mass-total radio luminosity plane. We combine FRI, FRII and compact samples of each excitation class to achieve the largest possible sample of HERGs to be compared with LERGs

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(of the same morphology). The results show that HERGs have younger stellar population (lower 4000$\AA$ break) with lower concentration and lower black hole mass than LERGs. They also reside in lower density, tidal interactions and PCA1 environment than those of LERGs. The results of this comparison confirms the previous studies [11] which showed HERG sources are located in star-forming disky galaxies and in low density environment compared to the LERGs which lie in bulge dominated galaxies and in dense environment. A preferred explanation is that black hole feeding mechanisms play the main role. LERGs are located in high density environments such as galaxy clusters where hot intergalactic gas is sufficiently available to feed the SMBH. This is also the place that elliptical galaxies have been formed. On the other hand HERGs are located in star forming galaxies in which cold gas is abundant and can feed the SMBH. Cold accretion in high rate results in highly excited features in the optical spectrum of radio galaxies while hot gas accretes mildly into the SMBH making LERGs.

4. Conclusion

We summarize the outcome of the above analysis as follows: The concentrated host galaxy and dense environment disrupt the radio jets creating FRI morphology compared to FRII morphology that is shaped in low density environment and low concentration host galaxies. Compared to the FRI/FRII radio galaxies that have extended emission, compact radio galaxies harbor lower mass black holes, that shows black hole mass influences launching the large scale radio jets. Black hole feeding mechanism is the main driver of HERG/LERG dichotomy.

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