

The environment of C- and S-shaped radio galaxies

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Abstract We study the environment of radio galaxies with different morphological types using the Proctor sample, which was built from the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) survey archive. Among the 15 radio galaxy types classified by Proctor, 199 C-shaped (i.e., wide- or narrow-angle tail) and 203 S-shaped (i.e., S- or Z-shaped) sources are selected in this work, which are located in the redshift range of $0.02 < z < 1$, because these two subsamples are relatively larger than the other subsamples in the Proctor sample. By cross-matching these radio galaxies with the optical sources drawn from the Sloan Digital Sky Survey (SDSS) database and counting the SDSS sources with an r -band absolute magnitude brighter than -19 located within a 0.5 Mpc distance around each source (i.e., the richness), we find that the fraction of C-shaped sources with a richness above 10 is larger than that of S-shaped sources. We have also correlated the radio galaxies in our sample with the brightest cluster galaxies (BCGs) defined in the NASA/IPAC Extragalactic Database (NED), and infer that the C-shaped sources are more likely to be BCGs than the S-shaped sources. These results support the idea that C-shaped radio galaxies often reside in a richer environment than radio galaxies with other morphological types.

Key words: galaxies: statistics — galaxies: structure — methods: data analysis

1 INTRODUCTION

The emissions of radio galaxies exhibit various morphologies, which may result from different host galaxy conditions or ambient environment, e.g., the size of the host galaxy (e.g., Miraghaei & Best 2017), the black hole to stellar mass ratio (e.g., Miraghaei & Best 2017), the motion of the central black hole (e.g., Florido et al. 1990), the intra-cluster medium (ICM) density (e.g., Begelman et al. 1984) and the environmental galaxy richness (e.g., Wing & Blanton 2011), i.e., a count of magnitude limited galaxies within a certain distance from the target source. Basically, there are two primary morphological classes of radio galaxies: Fanaroff-Riley type I and type II (FR I and FR II respectively; Fanaroff & Riley 1974). Typically, FR Is show a decreasing radio flux density at the plumes as the distance from the core increases, and FR IIs exhibit an inverse tendency with two bright hotspots at each end of the radio lobes.

Except for this rough classification, more complicated morphological taxonomies have been introduced in previous studies, including types such as wide- or narrow-angle tail sources (WATs or NATs respectively; e.g., Rudnick & Owen 1976), S- or Z-shaped sources (e.g., Florido et al. 1990), X-shaped sources (e.g., Leahy & Parma 1992; Cheung 2007), ring-like sources (e.g., Buta & Combes 1996), double-double sources that consist of two pairs of lobes with a common center (e.g., Schoenmakers et al. 2000a; Kaiser et al. 2000; Schoenmakers et al. 2000b) and others (e.g., hybrid morphology radio sources; Rudnick & Owen 1976).

In this work, we investigate the relationship between morphology and environment of radio galaxies. Only the C-shaped (i.e., WATs or NATs) and S-shaped (i.e., S- or Z-shaped) morphological types with sufficient sources that possess the highest fractions (21% and 20%, respectively) in a certain Proctor sample (Proctor 2011) classification are selected as our targets. The C-shaped morphology is

thought to be a direct result of ram pressure exerted on the jets when both the ICM density and relative velocity between the radio galaxy and ambient gas are high enough (Owen & Rudnick 1976; Eilek et al. 1984; Burns 1990; Ball et al. 1993; Bliton et al. 1998). The S-shaped morphology may be caused by a precessional central black hole, which causes changes in the orientation of the radio jet (Gower et al. 1982). The precession of the central black hole may be produced by the presence of a tilted accretion disk (Lu 1990; Lu & Zhou 2005), or another black hole in the same nucleus (Begelman et al. 1980). Because of the complex conditions that result in various morphologies, details on the formation of different morphological types of radio galaxies still need more investigation.

In order to study the impact of the environment on morphology, Zirbel (1997) studied the environment of FR sources and found that FR Is tend to reside in richer groups than FR IIs. By counting the number of galaxies with the Sloan Digital Sky Survey (SDSS) absolute r magnitude $M_r > -19$ within a radius of 1 Mpc around each radio source, and calculating the statistics of the richness distribution of the sources, Wing & Blanton (2011) confirmed that bent radio sources are more often found in richer clusters than non-bent radio sources. Miraghaei & Best (2017) investigated the properties of the host galaxies and environment, and found that compared with normal FR radio sources, the radio luminosity and host galaxy size of WATs are smaller, and the WATs tend to reside in denser regions than double-double and FR hybrid sources. The environment generally includes the ICM properties and richness; in this work, we choose to use the richness to indicate the environment.

This paper is organized as follows. In Section 2, we construct the sample and describe how to determine the optical counterparts of radio galaxies. Section 3 presents measurement of the richness around each radio source. In Section 4, we cross-match our sources with the brightest cluster galaxies (BCGs) using five galaxy cluster catalogs to determine the BCG proportions of the C- and S-shaped radio galaxies in our sample. In Section 5, we study physical properties of the radio galaxies. A brief summary is provided in Section 6. The Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$ is adopted in this paper.

2 SAMPLE CONSTRUCTION

2.1 Selection of Radio Galaxies

The Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) survey covers over 10 000 square degrees of the sky that overlaps the SDSS area, with a flux density threshold of 1 mJy and a resolution of $5''$. Radio galax-

ies in FIRST have been classified into 15 types by Proctor (2011) according to their morphology. We use the 412 C-shaped sources and 400 S-shaped sources that belong to the Proctor sample to construct the initial sample for our research.

2.2 Optical Counterparts

Optical sources in the SDSS Data Release 14 (DR14) (Abolfathi et al. 2018) are used for cross-matching the radio sources. Following the procedure presented in Wing & Blanton (2011), we first match each galaxy in our sample with the SDSS sources within a separation of $10''$. The number of cross-matched radio sources of the two subsamples is set as a function of separation. Wrong cross-matchings could exist, because the projection of unrelated optical sources may be located within a small separation from the radio galaxies. To estimate the wrong matches, we shift both the right ascension (R.A.) and declination (Dec.) of each radio source by adding $30'$; all the shifted coordinates will be physically unrelated to their former SDSS counterparts. Then we match the shifted coordinates with the SDSS sources as in previous steps to achieve random matches at different matching separations. The random matches are not real radio-optical counterparts, but give an estimation of possible wrong matches at each separation. The number of random matches is also set as a function of the separation between counterparts.

The upper and lower panels in Figure 1 illustrate cross-matching procedures for the C-shaped and S-shaped sources, respectively, and the left panels show the cross-matched number as a function of separation. Both of the real matches display peaks appearing below a separation of $1''$, but the random matches increase slowly as the separation increases, which is the result of the increasing cross-matching area as the separation increases. In the right panels, the solid lines signify the cumulative real matches corresponding to the left panels, as a function of separation. The dot-dashed lines represent cumulative good matches, which are the cumulative real matches minus the cumulative random matches, as a function of separation. The dashed lines indicate the matching reliability of the subsamples, which is the value of cumulative good matches divided by cumulative real matches. We expect a 90% reliability cutoff, which corresponds to a separation of about $3.3''$ for C-shaped sources and $4.2''$ for S-shaped sources. So, the matching separation limits of $3.3''$ and $4.2''$ are determined for the C-shaped and S-shaped subsamples, respectively. Finally, the sample contains 199 C-shaped sources and 203 S-shaped sources in the redshift range $0.02 < z < 1$ after the cross-matching steps. The sources are listed in Table 1.

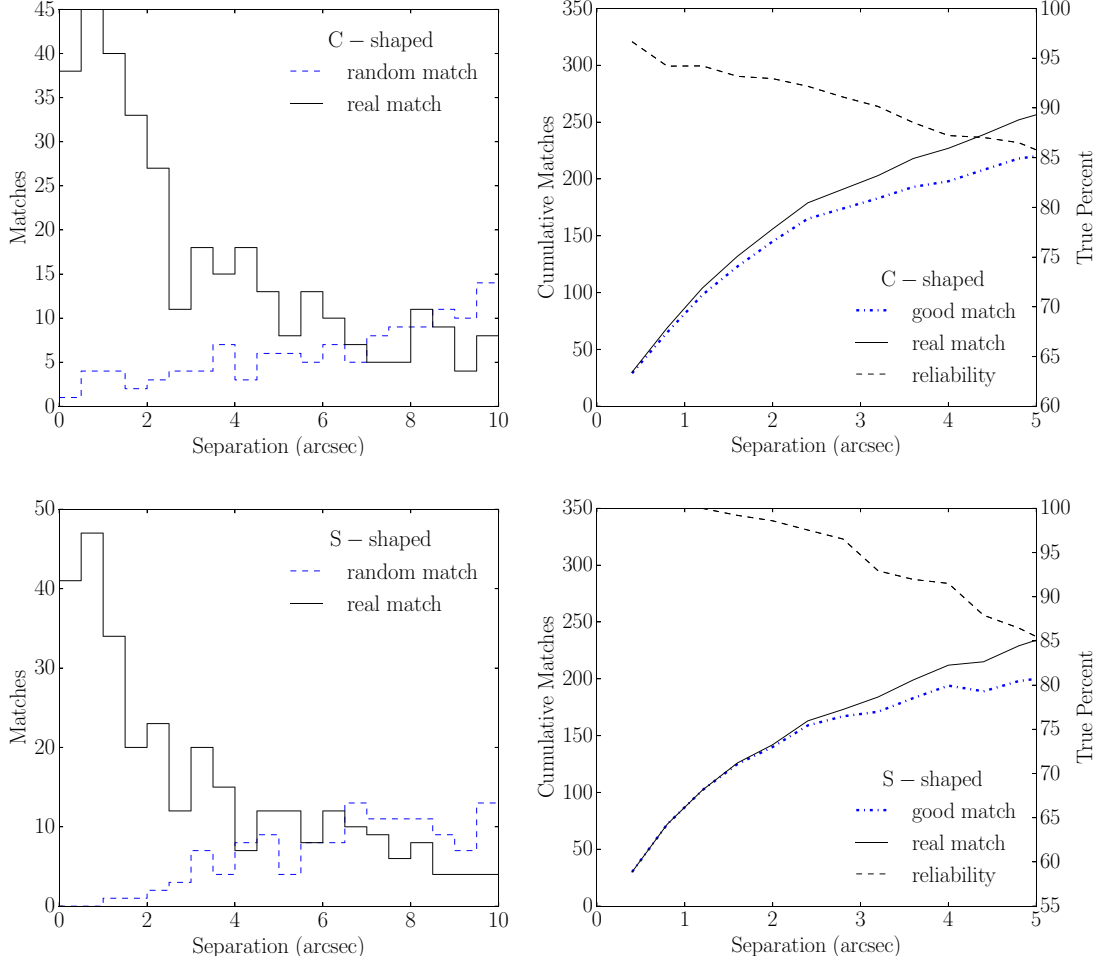


Fig. 1 The upper and lower panels illustrate cross-matching procedures of the C-shaped and S-shaped sources, respectively. In the left panels, the *solid line histograms* represent the number of C-shaped or S-shaped radio-optical matches, as a function of separation. The *dashed line histograms* mean distributions of random matches for the shifted subsamples. In the right panels, the *solid lines* show the cumulative matches of C-shaped or S-shaped sources, as a function of separation. The *dot-dashed lines* correspond to cumulative good matches that are the cumulative real matches minus the cumulative random matches. The *dashed lines* signify the percentage of true matches.

3 RICHNESS OF THE SELECTED RADIO GALAXIES

3.1 Definition of Richness

We choose the richness measurement system similar to those adopted in the previous works (Allington-Smith et al. 1993; Zirbel 1997; Blanton et al. 2000), where the richness $N_{0.5}^{-19}$ represents the number of galaxies with absolute visual magnitude $M_V > -19$ within a 0.5 Mpc distance around a radio galaxy. Since we draw data from SDSS catalogs, the SDSS r -band absolute magnitude is adopted, and the richness $N_{0.5}^{-19}$ is defined as the number of galaxies brighter than $M_r = -19$ within a 0.5 Mpc radius circle centered on a radio galaxy.

3.2 Background Galaxy Density

To estimate the richness, the background galaxies should be subtracted from the total number counts within the 0.5 Mpc circle. The large number of sources in the SDSS field of view provides us with an approach for counting background galaxies. We use the spectroscopic redshift whenever it is available, otherwise, the photometric redshift is used. For a small fraction of sources with no redshift information in SDSS DR14, the redshifts in DR8 (Aihara et al. 2011) are adopted. The k -corrections are calculated following the method provided in Blanton & Roweis (2007), and the extinctions in the SDSS catalog are also considered to correct the absolute magnitudes (Schlegel et al. 1998).

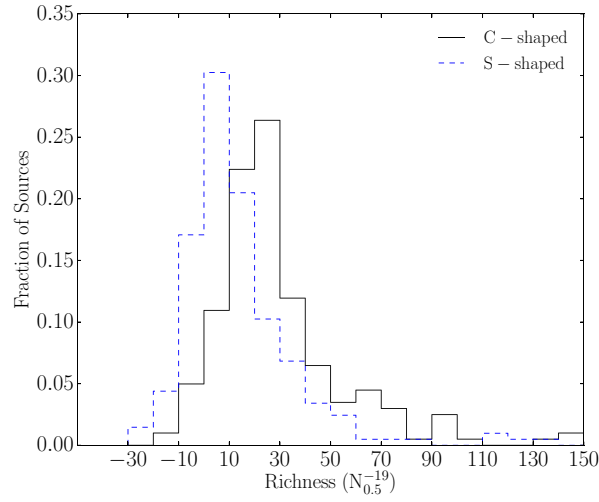


Fig. 2 The fraction of sources as a function of richness for the C- and S-shaped sources. The *solid line histogram* represents C-shaped sources and the *dashed line histogram* signifies S-shaped sources.

Table 1 The Sample

Name	R.A. (J2000)	Dec. (J2000)	Redshift	Type	m_r (mag)	M_r (mag)	$\log_{10}(L_{1.4\text{G}})$ (W Hz $^{-1}$)	Extent (Mpc)	$N_{0.5}^{-19}$	f_c	GC1str
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
J000330.7+002756	00h03m30.73s	+00d27m56.0s	0.19199 ^S	C	17.07	−22.93	24.62	0.17	21	1.00	WHL
J002216.5+010403	00h22m16.56s	+01d04m03.2s	0.53402 ^S	S	20.30	−23.21	25.59	0.18	−1	1.49	
J003432.6−093444	00h34m32.61s	−09d34m44.5s	0.46118 ^P	S	19.93	−22.86	25.21	0.09	4	1.28	
J004152.1+002837	00h41m52.10s	+00d28m37.3s	0.15199 ^S	C	16.46	−22.87	24.79	0.11	25	1.00	WHL
J010236.5−005007	01h02m36.57s	−00d50m07.6s	0.24331 ^S	C	17.65	−22.97	24.96	0.11	29	1.00	RM
J010242.4−005032	01h02m42.42s	−00d50m32.9s	0.24281 ^S	C	17.64	−22.99	25.18	0.19	24	1.00	WHL
J010403.0−002440	01h04m03.04s	−00d24m40.9s	0.28307 ^S	C	17.90	−23.23	25.52	0.22	19	1.00	
J011425.5+002932	01h14m25.59s	+00d29m32.5s	0.35461 ^S	C	18.45	−23.32	25.60	0.19	19	1.07	WHL
J012947.0+004633	01h29m47.03s	+00d46m33.4s	0.42151 ^P	C	21.01	−21.80	25.51	0.21	−1	1.19	
J013247.1+011545	01h32m47.16s	+01d15m45.4s	0.12560 ^S	C	15.16	−23.68	24.99	0.14	48	1.00	WHL
J020613.2−021504	02h06m13.27s	−02d15m04.6s	0.34877 ^P	S	19.42	−22.26	25.00	0.11	10	1.06	
J021534.3−032202	02h15m34.36s	−03d22m02.7s	0.76463 ^P	S	22.74	−22.24	26.47	0.24	−11	2.84	
J021619.7−024433	02h16m19.75s	−02d44m33.5s	0.06952 ^S	C	14.97	−22.43	24.56	0.10	17	1.00	WHL
J024558.4−064859	02h45m58.45s	−06d48m59.9s	0.13857 ^S	C	16.52	−22.58	24.78	0.14	28	1.00	
J024612.8−084735	02h46m12.81s	−08d47m35.8s	0.13816 ^S	C	16.52	−22.58	24.83	0.13	16	1.00	
J031147.3+010846	03h11m47.36s	+01d08m46.6s	0.21192 ^S	C	18.54	−21.98	24.42	0.10	23	1.00	
J031357.1−001531	03h13m57.13s	−00d15m31.2s	0.31706 ^S	S	18.62	−22.93	25.26	0.16	5	1.02	
J071501.6+404820	07h15m01.68s	+40d48m20.3s	0.51359 ^P	S	21.51	−21.59	25.55	0.17	10	1.42	
J072725.1+310934	07h27m25.14s	+31d09m34.6s	0.24987 ^P	C	18.41	−22.37	25.92	0.35	28	1.00	
J073202.4+274530	07h32m02.41s	+27d45m30.9s	0.36894 ^P	S	19.27	−22.70	25.26	0.20	11	1.09	
J073229.7+374420	07h32m29.76s	+37d44m20.1s	0.20121 ^S	C	17.49	−22.68	24.84	0.08	49	1.00	GMBCG
J073441.9+361129	07h34m41.93s	+36d11m29.5s	0.43209 ^S	C	19.60	−22.98	25.50	0.16	5	1.21	WHL
J073539.8+251020	07h35m39.80s	+25d10m20.3s	0.07873 ^P	C	15.10	−22.64	24.38	0.09	18	1.00	WHL
J073540.4+361912	07h35m40.47s	+36d19m12.7s	0.12015 ^P	C	16.47	−22.31	24.45	0.03	35	1.00	
J073618.0+241043	07h36m18.00s	+24d10m43.9s	0.14710 ^S	C	16.39	−22.93	25.39	0.17	46	1.00	WHL
J073837.7+482046	07h38m37.74s	+48d20m46.7s	0.09523 ^P	S	15.75	−22.56	23.74	0.03	6	1.00	
J074041.9+345843	07h40m41.95s	+34d58m43.3s	0.57113 ^S	S	20.10	−23.87	25.58	0.35	0	1.62	
J074115.4+163254	07h41m15.49s	+16d32m54.1s	0.10132 ^S	C	16.17	−22.15	23.68	0.05	69	1.00	
J074118.0+163156	07h41m18.02s	+16d31m56.8s	0.10029 ^P	C	15.75	−22.55	23.86	0.08	70	1.00	WHL
J074143.0+174056	07h41m43.04s	+17d40m56.9s	0.12360 ^P	C	16.07	−22.76	24.53	0.15	11	1.00	

The full table is online at <http://www.raa-journal.org/docs/Supp/ms4370table1.pdf>.

We follow the procedure provided in Wing & Blanton (2011) to count galaxies brighter than $M_r = -19$ within an annulus whose inner and outer radii are 2.7 Mpc and 3 Mpc, respectively, centered on the core of each radio source. Most galaxies located in this distant annulus are expected to be unassociated with the potential cluster (Wing

& Blanton 2011). The galaxy density within the annulus is set as the background density, which should be subtracted from the total density derived within the 0.5 Mpc radius circle. The richness $N_{0.5}^{-19}$ is obtained by multiplying the area within the 0.5 Mpc circle and the subtracted galaxy density.

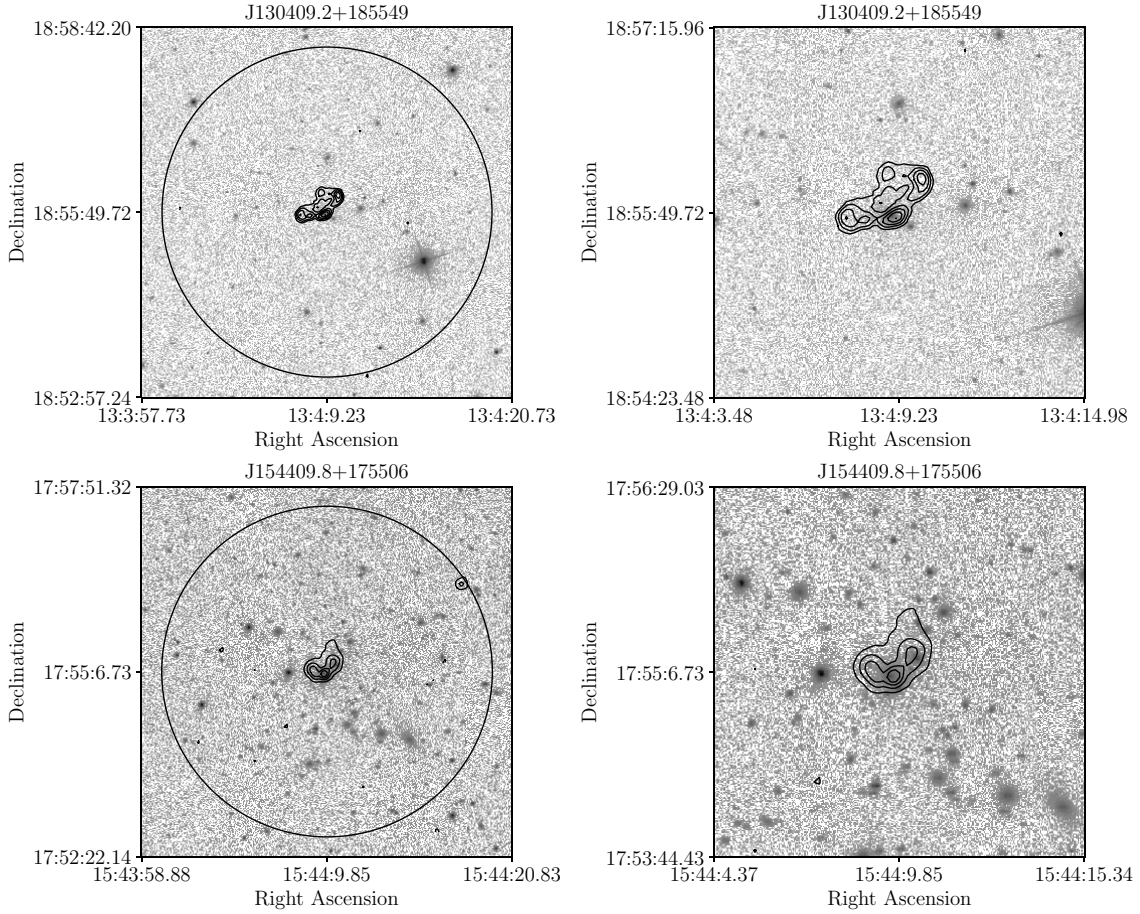


Fig. 3 FIRST contours and SDSS r -band images. The radio emission maps are square root scaled with four contours, with minimum contours of 0.5 mJy and maximum contours of 3.4 mJy and 36.6 mJy for the upper and lower panels, respectively. The *circles* centered on the sources with 0.5 Mpc radius are shown in the left panels, and the corresponding centered 0.5×0.5 Mpc areas are displayed in the right panels. The top panels feature a C-shaped source located at redshift $z = 0.197$ with $N_{0.5}^{-19} = 3$. The bottom panels depict a C-shaped source located at redshift $z = 0.209$ with $N_{0.5}^{-19} = 63$.

3.3 Schechter Correction

The limiting SDSS r -band magnitude is $m_r \sim 22$, since sources with absolute magnitude $M_r = -19$ cannot be detected above redshift $z \sim 0.3$. Thus the richness we obtain from the previous steps may be smaller than the real one. In order to estimate the richness around the higher redshift sources, the raw richness should be multiplied by a Schechter correction factor to give a corrected richness measurement (Hill & Lilly 1991; Zirbel 1997; Blanton et al. 2000; Wing & Blanton 2011). According to Wing & Blanton (2011), the correction factor is defined as

$$f_c = \phi(M_r) / \phi(M_{r,\text{lim}}), \quad (1)$$

where $\phi(M)$ is the integrated Schechter luminosity function, which predicts the number of expected galaxies brighter than a given magnitude (Schechter 1976), $M_r = -19$ represents the faint end of absolute magnitude in the richness definition and $M_{r,\text{lim}}$ denotes the absolute magnitude corresponding to the limiting SDSS magnitude ($m_r \sim$

22) at the redshift of the target source. The correction factor calculated by the mean Schechter luminosity function may be a little rough for the radio sources located in galaxy clusters. We adopt the Schechter luminosity function with parameters $M_r^* = -21.48$ and $\alpha = -1.26$, based on the results of Montero-Dorta & Prada (2009). When the sources in our sample have redshifts below $z \sim 0.3$, all galaxies at those redshifts with absolute magnitudes brighter than $M_r = -19$ could be detected even at the limiting magnitude of SDSS, and thus the correction factor is set as $f_c = 1$.

3.4 Richness Measurement and Results

After the Schechter correction is applied, we obtain the richness around the radio sources. Figure 2 shows the fraction of sources as a function of richness. We find that when the richness $N_{0.5}^{-19} \geq 10$, the cumulative fraction of C-shaped sources is 82.9%, which is larger than 46.3% of the S-shaped ones. We define galaxies with richness $N_{0.5}^{-19} <$

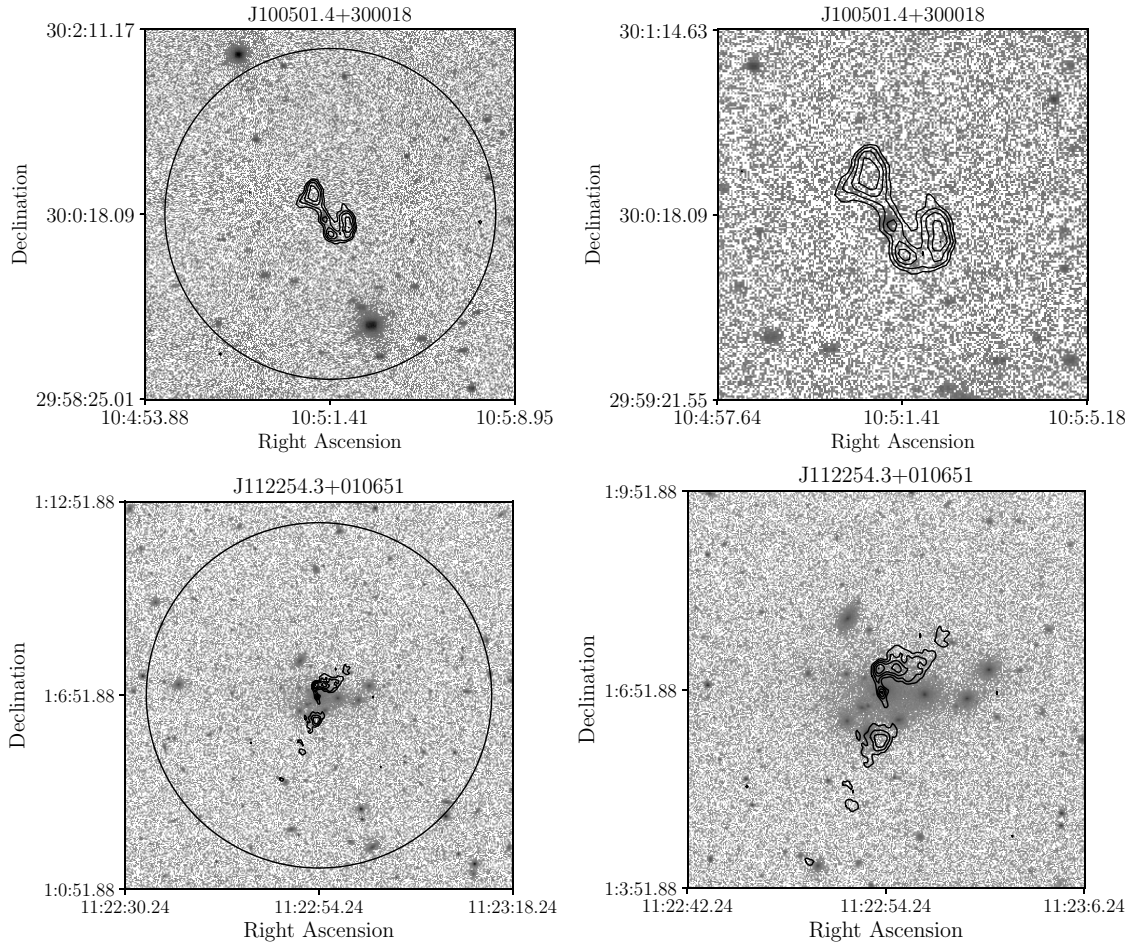


Fig. 4 FIRST contours and SDSS r -band images. The radio emission maps are square root scaled with four contours, with minimum contours of 0.5 mJy and maximum contours of 1.7 mJy and 6.3 mJy for the upper and lower panels, respectively. The *circles* centered on the sources with 0.5 Mpc radius are shown in the left panels, and the corresponding centered 0.5×0.5 Mpc areas are displayed in the right panels. The top panels feature an S-shaped source located at redshift $z = 0.353$ with $N_{0.5}^{-19} = 3$. The bottom panels depict an S-shaped source located at redshift $z = 0.083$ with $N_{0.5}^{-19} = 87$.

10 as residing in a poor environment. When $N_{0.5}^{-19} < 0^1$, the fraction of C-shaped sources is 6.0% and it is 23.2% for S-shaped sources. The average richness is $N_{0.5}^{-19} \sim 29$ for the C-shaped sources, and $N_{0.5}^{-19} \sim 13$ for S-shaped ones (Fig. 2). Using the Kolmogorov-Smirnov (K-S) test, we examine the likelihood of the richness distribution for the C-shaped and S-shaped subsamples being identical, and find that the P value is $2.47 \times 10^{-17}\%$. Therefore, compared with S-shaped sources, C-shaped ones are significantly more likely to be located in a richer environment. Four examples of C-shaped and S-shaped sources and their environments are shown in Figures 3 and 4 respectively.

We compare this result with that of Wing & Blanton (2011) in which the C-shaped radio galaxies are denoted as bent sources with multiple-components. Most bent sources

used in that paper are not certainly classified as C-shaped sources in the Proctor sample, but are given a probability of being bent, e.g., the source J075718.7+345905 with a probability of 2% of being bent in the Proctor sample is treated as a bent source in Wing & Blanton (2011). About 71% of bent radio galaxies reside in a cluster environment, while the fraction is 44% for non-bent sources (Wing & Blanton 2011). Therefore, both Wing & Blanton (2011) and our results support the idea that bent radio galaxies often reside in richer environments than non-bent radio sources.

4 CORRELATION BETWEEN A RADIO SOURCE AND THE CORRESPONDING BCG

As another way to investigate the environmental differences between C-shaped and S-shaped radio galaxies, we investigate the proportion of sources that are BCGs in the galaxy clusters.

¹ Negative values of richness indicate that within 0.5 Mpc from the radio galaxies, the local galaxy density is lower than the background galaxy density (Wing & Blanton 2011).

We cross-match the radio sources with the BCGs in all sample clusters, which are defined using data from the NASA/IPAC Extragalactic Database (NED) with an offset of $3''$. The cross-matched BCG catalogs include the WHL (Wen et al. 2009), Gaussian Mixture Brightest Cluster Galaxy (GMBCG; Hao et al. 2010), MaxBCG (Koester et al. 2007), [EAD2007] (Estrada et al. 2007) and redMaP-Per (RM; Rozo et al. 2015). We find that 51.8% (103 out of 199) of C-shaped radio sources have BCG identities, but only 15.8% (32 out of 203) of S-shaped sources are BCGs. Thus the C-shaped sources are more likely to be the BCGs of galaxy clusters than the S-shaped sources. This is not only consistent with the result in Section 3 that C-shaped sources often reside in a richer environment than S-shaped sources, but also confirms the idea that C-shaped radio galaxies are usually associated with the corresponding BCGs (Burns 1981).

Nearly all sources with BCG identities have positive richness values, except for the three C-shaped galaxies, J080611.3+253138, J102228.2+165315 and J145022.4+272820. J080611.3+253138 is a source in the MaxBCG catalog at redshift $z \sim 0.17$, possibly because the richness definition used by Koester et al. (2007) to search for BCGs (i.e., the number of sources brighter than $0.4L_*$ in the SDSS i -band within a radius of R_{200}) is different from ours. It is the same case with the other two BCG sources (J102228.2+165315 and J145022.4+272820) having negative richness values. Note that a galaxy cluster included in one catalog may not be included in another one due to different richness definitions (e.g., the galaxy J080611.3+253138, the poorest cluster whose richness is 10 in the MaxBCG catalog, is unrelated to the cluster in the GMBCG catalog).

We summarize our results in Table 1, where the source names are shown in column 1, the R.A. and Dec. of the sources in J2000 coordinates in columns 2 and 3 respectively, the redshift of the sources (with the superscripts S for spectroscopic redshift and P for photometric redshift) in column 4, the types of source (C for C-shaped and S for S-shaped) in column 5, the SDSS r -band magnitude of the sources in column 6, the r -band absolute magnitude in column 7, the radio luminosity in 1.4 GHz in column 8, the radio source extent (see the text for the definition) in column 9, the richness in column 10, the correction factors in column 11 and the catalogs of the cross-matched BCGs in column 12.

5 PHYSICAL PROPERTIES OF C-SHAPED AND S-SHAPED RADIO SOURCES

We investigate the physical properties of the sources, such as whether or not radio source extent and luminosity

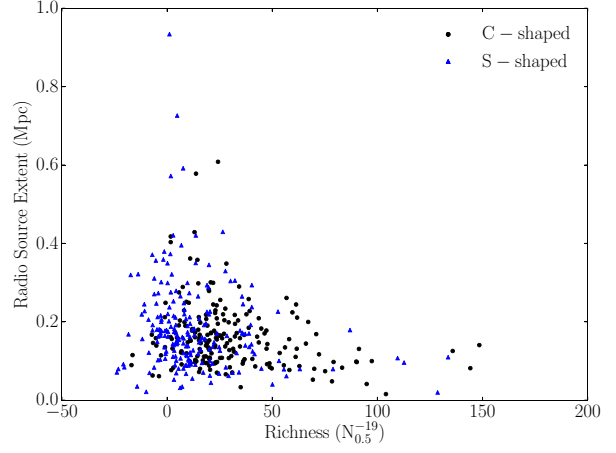


Fig. 5 Richness vs. radio source extent. The *triangle symbols* represent S-shaped sources and the *circle symbols* signify C-shaped sources.

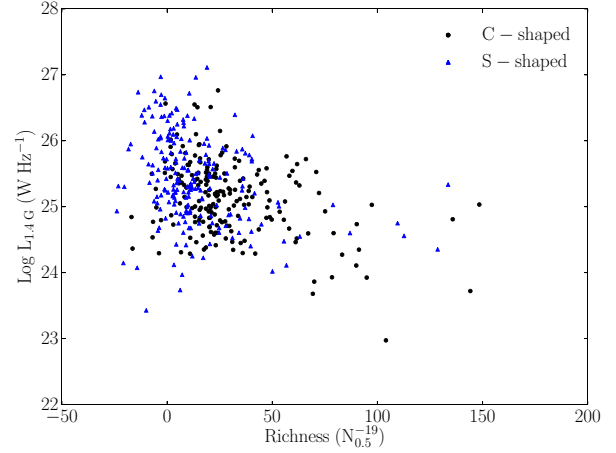


Fig. 6 Relationship between richness and radio luminosity at 1.4 GHz of the radio sources. The symbols are the same as in Fig. 5.

are correlated with richness. The radio source extent of the galaxies is defined as the projected distance between the core and the farthest edge of lobes or plumes in the FIRST images. Figure 5 shows the relationship between richness and source extent of the galaxies. The radio source extent of most galaxies is smaller than 0.5 Mpc, the scale used to calculate the richness. Four giant S-shaped radio galaxies (J083448.7+173651, J135517.6+292333, J141621.7+590032 and J160420.0+373117), whose source extents are larger than 0.5 Mpc, reside in a poor environment with $N_{0.5}^{-19} < 10$, and two giant C-shaped radio galaxies (J124619.2+262635 and J155806.8+451955) reside in a richer environment with richness $N_{0.5}^{-19} > 10$. All radio galaxies with richness $N_{0.5}^{-19} > 50$ possess a source extent smaller than 0.3 Mpc, i.e., radio sources that are located in a very rich environment tend to exhibit small sizes, a tendency that is more obvious for the C-shaped sources as shown in Figure 5.

The 1.4 GHz radio luminosities of the sources are also calculated using the radio flux densities from the catalog of Condon et al. (1998). Figure 6 illustrates the radio luminosities of the sources against the richness. There is no obvious correlation between radio luminosity and richness, which agrees with the conclusion of Zirbel (1997).

6 SUMMARY

We have selected C-shaped and S-shaped radio galaxies from the Proctor sample and cross-matched them with SDSS sources. Then we calculated the richness around each source to study differences in the environment between C-shaped and S-shaped radio galaxies. Moreover, the correlation between these radio galaxies and the BCGs has been investigated. Based on these results, we draw the conclusions that the fraction of C-shaped sources with richness $N_{0.5}^{-19} \geq 10$ is 82.9%, which is significantly larger than 46.3% for S-shaped sources. That is, C-shaped sources tend to be located in richer environments than S-shaped sources. About 51.8% of C-shaped sources are the BCGs of galaxy clusters, which is larger than 15.8% of S-shaped sources with BCG identities. Enlargement of the two subsamples will be helpful for confirming the conclusions and providing a better understanding of the relationship between the morphologies of radio galaxies and their surrounding environments.

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References

- Abolfathi, B., Aguado, D. S., Aguilar, G., et al. 2018, *ApJS*, 235, 42
- Aihara, H., Allende Prieto, C., An, D., et al. 2011, *ApJS*, 193, 29
- Allington-Smith, J. R., Ellis, R., Zirbel, E. L., & Oemler, Jr., A. 1993, *ApJ*, 404, 521
- Ball, R., Burns, J. O., & Loken, C. 1993, *AJ*, 105, 53
- Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, *Nature*, 287, 307
- Begelman, M. C., Blandford, R. D., & Rees, M. J. 1984, *Reviews of Modern Physics*, 56, 255
- Blanton, E. L., Gregg, M. D., Helfand, D. J., Becker, R. H., & White, R. L. 2000, *ApJ*, 531, 118
- Blanton, M. R., & Roweis, S. 2007, *AJ*, 133, 734
- Bliton, M., Rizza, E., Burns, J. O., Owen, F. N., & Ledlow, M. J. 1998, *MNRAS*, 301, 609
- Burns, J. O. 1981, *MNRAS*, 195, 523
- Burns, J. O. 1990, *AJ*, 99, 14
- Buta, R., & Combes, F. 1996, *Fund. Cosmic Phys.*, 17, 95
- Cheung, C. C. 2007, *AJ*, 133, 2097
- Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, *AJ*, 115, 1693
- Eilek, J. A., Burns, J. O., O’Dea, C. P., & Owen, F. N. 1984, *ApJ*, 278, 37
- Estrada, J., Annis, J., Diehl, H. T., et al. 2007, *ApJ*, 660, 1176
- Fanaroff, B. L., & Riley, J. M. 1974, *MNRAS*, 167, 31P
- Florido, E., Battaner, E., & Sanchez-Saavedra, M. L. 1990, *Ap&SS*, 164, 131
- Gower, A. C., Gregory, P. C., Unruh, W. G., & Hutchings, J. B. 1982, *ApJ*, 262, 478
- Hao, J., McKay, T. A., Koester, B. P., et al. 2010, *ApJS*, 191, 254
- Hill, G. J., & Lilly, S. J. 1991, *ApJ*, 367, 1
- Kaiser, C. R., Schoenmakers, A. P., & Röttgering, H. J. A. 2000, *MNRAS*, 315, 381
- Koester, B. P., McKay, T. A., Annis, J., et al. 2007, *ApJ*, 660, 239
- Leahy, J. P., & Parma, P. 1992, in *Extragalactic Radio Sources. From Beams to Jets*, eds. J. Roland, H. Sol, & G. Pelletier, 307
- Lu, J. F. 1990, *A&A*, 229, 424
- Lu, J.-F., & Zhou, B.-Y. 2005, *ApJ*, 635, L17
- Miraghaei, H., & Best, P. N. 2017, *MNRAS*, 466, 4346
- Montero-Dorta, A. D., & Prada, F. 2009, *MNRAS*, 399, 1106
- Owen, F. N., & Rudnick, L. 1976, *ApJ*, 205, L1
- Proctor, D. D. 2011, *ApJS*, 194, 31
- Rozo, E., Rykoff, E. S., Becker, M., Reddick, R. M., & Wechsler, R. H. 2015, *MNRAS*, 453, 38
- Rudnick, L., & Owen, F. N. 1976, *ApJ*, 203, L107
- Schechter, P. 1976, *ApJ*, 203, 297
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
- Schoenmakers, A. P., de Bruyn, A. G., Röttgering, H. J. A., & van der Laan, H. 2000b, *MNRAS*, 315, 395
- Schoenmakers, A. P., de Bruyn, A. G., Röttgering, H. J. A., van der Laan, H., & Kaiser, C. R. 2000a, *MNRAS*, 315, 371
- Wen, Z. L., Han, J. L., & Liu, F. S. 2009, *ApJS*, 183, 197
- Wing, J. D., & Blanton, E. L. 2011, *AJ*, 141, 88
- Zirbel, E. L. 1997, *ApJ*, 476, 489