Research in Astronomy and Astrophysics, 23:035005 (8pp), 2023 March https://doi.org/10.1088/1674-4527/acb251

Three New Spiral Galaxies with Active Nuclei Producing Double Radio Lobes

X. Y. Gao[1,2,3], Z. S. Yuan[1,2], J. L. Han[1,2,3], Z. L. Wen[1,2,3], and S. S. Shan[1,3]
[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; xygao@nao.cas.cn, hjl@nao.cas.cn
[2] CAS Key Laboratory of FAST, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China
[3] School of Astronomy, University of Chinese Academy of Sciences, Beijing 100049, China
Received 2022 November 2; revised 2022 December 26; accepted 2023 January 3; published 2023 February 14

Abstract

Double radio lobes are generally believed to be produced by active nuclei of elliptical galaxies. However, several double-lobed radio sources have been solidly found to be associated with spiral galaxies. By cross-matching $\sim 9 \times 10^5$ spiral galaxies selected from the Sloan Digital Sky Survey DR8 data with the full 1.4 GHz radio source catalogs of NRAO VLA Sky Survey and Faint Images of the Radio Sky at Twenty-centimeters, we identify three new spiral galaxies: J0326−0623, J1110+0321 and J1134+3046 that produce double radio lobes, and five double-lobed spirals previously known. By combining the newly discovered and all the other known cases in literature, we confirm the relation that more massive spiral galaxies could produce more powerful radio lobes. We find that most of these spiral galaxies are located in a galaxy group or a poor cluster, in which the environment is denser than in the field, and about half of them are the central brightest galaxies in their parent system. We therefore suggest that the environment is one of the key factors for a spiral to produce double radio lobes.

Key words: radio continuum: galaxies – galaxies: active – galaxies: jets – galaxies: ISM

1. Introduction

Radio lobes powered by the supermassive black hole (SMBH) in the centers of galaxies are usually hosted by elliptical galaxies. They extend to several hundred kiloparsecs which are much larger than their optical counterparts. The point of view that double radio lobes are exclusively hosted by elliptical galaxies has been challenged by the discovery of the double-lobed radio source J0313−192 (J0315−1906), which was found to be hosted by a *spiral* galaxy (Ledlow et al. 1998, 2001; Keel et al. 2006).

In the last two decades, a few more spiral galaxies hosting double radio lobes have been revealed. Hota et al. (2011) discovered the second case, Speca (J1409−0302), which has episodic radio emission. Bagchi et al. (2014) identified J2345 −0449 with lobes extending to an extraordinary length of ∼1.6 Mpc. Mulcahy et al. (2016) reported the serendipitous discovery of the double radio source MCG+07–47–10 (J2318 +4314) with a low luminosity of $P_{1.4\,\mathrm{GHz}} \sim 10^{22}$ W Hz^{-1}. Very recently, Vietri et al. (2022) identified a new source J0354 −1340 with double radio lobes extending approximately 240 kpc.

Searches for spiral galaxies with double radio lobes have also been made systematically by several groups. Mao et al. (2015) cross-matched the optical Galaxy Zoo "superclean" sample (Lintott et al. 2008) with the Unified Radio Catalog of Kimball & Ivezić (2008), which includes radio sources from both the Faint Images of the Radio Sky at Twenty-centimeters (FIRST, Becker et al. 1995) and the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) data. They reported a new spiral J1649+2635 with double radio lobes, which has a radio power of about 10^{24} W Hz^{-1} at 1.4 GHz. Singh et al. (2015) cross-matched the FIRST catalog (Becker et al. 1995) with the 187,005 spiral galaxies (Meert et al. 2015) from the Sloan Digital Sky Survey (SDSS, York et al. 2000) Data Release 7 (DR7) to search for coincidences of a core source within a radius of 3″ and also the double lobes within a radius of 3′. They conducted an additional search for the extended radio lobes with the NVSS data (Condon et al. 1998) for the obtained FIRST-SDSS matched objects and identified four spiral galaxies with double radio lobes, among which J1159+5820 (Kozieł-Wierzbowska et al. 2012), J1352+3126 (Donzelli et al. 2007) and J1649+2635 (Mao et al. 2015) were already reported previously, while J0836+0532 was found for the first time. Ortiz Martínez & Andernach (2016) collected 675,874 spiral galaxies from several spiral galaxy samples (e.g., Huertas-Company et al. 2011; Willett et al. 2013; Kuminski & Shamir 2016), and searched for the associated FIRST sources (Becker et al. 1995) within a larger radius of 6′ under constraints of angular distances, position angles and arm-length ratio of the double radio sources with respect to the central optical galaxy. Concentrating on the extremely symmetric and aligned radio lobes, they finally reported the re-discovery of the known case of J1649+2635 (Mao et al. 2015). Though these efforts have been dedicated to searching for the spiral galaxies hosting double radio lobes, only a handful of cases have been confirmed to date.

It is also unclear why these spirals produce double radio lobes while the vast majority of other spirals do not. Often radio lobes may be triggered by the accretion of host galaxies from the overdense environments in their vicinity. For example, the source J0315−1906 is a member galaxy of the cluster A428 (Ledlow et al. 1998). J1409−0302 and J1649+2635 are the brightest galaxies of their parent systems (Hota et al. 2011; Mao et al. 2015), and J2318+4314 is located close to the galaxy groups NGC 7618 and UGC 12491 (Mulcahy et al. 2016). However, Singh et al. (2015) found that J0836+0532 and J1352+3126 are in galaxy groups with very limited members and listed them as field galaxies together with J1159+5820 (see their Table 7). Therefore, a large sample of such galaxies is needed to investigate the environmental effect on radio lobes. Wu et al. (2022) recently analyzed optical images from the Hubble Space Telescope of a sample of galaxies with extended double radio lobes seen from FIRST (Becker et al. 1995), and found that 18 disk galaxies have high probability of genuine association. Some of these disk galaxies have a small inclination angle and show clear spiral patterns.

We notice that Kuminski & Shamir (2016) classified the broad morphological types of $\sim 3 \times 10^6$ galaxies in the SDSS (York et al. 2000) Data Release 8 (DR8) by analyzing images of galaxies with computer programs, and their pipeline picked out $\sim 9 \times 10^5$ spiral galaxies. Here, we take this large sample as the optical basis of spiral galaxies, and cross-match them with the full radio source catalogs of NVSS (Condon et al. 1998) and FIRST (Becker et al. 1995). We discover three new and re-identify five known spiral galaxies with double radio lobes. The paper is organized as follows. In Section 2, we introduce the data sets used to identify the double-lobed spiral galaxies, and also the procedure of identification. We show the results and discuss the properties of the galaxies and their environments in Section 3. The concluding remarks are given in Section 4.

Throughout the paper, we adopt a flat ΛCDM cosmology with $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2. Data and Search Strategy

2.1. Data

Via an automatic computer program, Kuminski & Shamir (2016) classified approximately 9×10^5 spiral galaxies out of $\sim 3 \times 10^6$ galaxies observed in the SDSS (York et al. 2000) DR8. The classifications for spiral galaxies and elliptical galaxies show good agreement with those of the Galaxy Zoo debiased "superclean" sample (Lintott et al. 2008) and the agreement rate is claimed to reach 98% when the "classification certainty" $p \geqslant 0.54$.

Two catalogs were released by Kuminski & Shamir (2016). The "catalog.dat"[4] is the catalog of the broad morphology of SDSS galaxies with only the classification certainty p indicated, and the "spec.dat" including both indications of "p" and morphological remarks (Elliptical, Spiral, Star) is the morphological catalog of the SDSS objects with spectra. In this work, we first take all the spiral galaxies in the two catalogs with $p \geqslant 0.54$. However, we notice that some known spirals such as J0836+0532 and J1649+2635, as shown in Table 1, have a classification certainty of $p = 0.23$ and $p = 0.37$, respectively, less than 0.54. In order not to miss many real spirals, we simply include all galaxies marked as "Spiral" in the "spec.dat" of Kuminski & Shamir (2016), regardless of the values of p. Therefore, all 366,836 entries in the "spec.dat" marked as "Spiral" and 1,184,922 entries with $p \geqslant 0.54$ in "catalog.dat" are used to search for associated double radio lobes. The duplicates in the two catalogs are treated at the final stage when inspecting the association between optical and radio images.

The radio counterparts of the optical spiral galaxies are searched in the NVSS (Condon et al. 1998) and FIRST (Becker et al. 1995) source catalogs. The NVSS was carried out with the Very Large Array (VLA)—D configuration at the frequency of 1.4 GHz with an angular resolution of $\sim 45''$. The survey covers the entire sky north of decl. $\delta = -40°$. Over 1.8 million discrete sources brighter than ~ 2.5 mJy (5σ level) were compiled into the associated catalog[5]. The positional accuracy of NVSS is about $1''$ for strong sources and $7''$ for faint sources. The FIRST observations were conducted at the same frequency, but with a much better angular resolution of $\sim 5''$ by using the VLA—B configuration array. It has a sensitivity of about 0.13 mJy beam^{-1}. The sky coverage of FIRST is limited within the northern and southern Galactic cap regions of about 10,000 square degrees in total, which is less than one third that of NVSS. The FIRST catalog contains over 9.4×10^5 entries. For the sources whose flux density is higher than 1 mJy, the radius of the 90% positional confidence error circle is less than $1''$. The latest FIRST source catalog of Version 14Dec17[6] is used in this study.

2.2. Search Strategy

Based on the experiences gained from previous work (e.g., Yuan et al. 2016), we learned that the $5''$ angular resolution of FIRST could resolve out extended radio structures so that diffuse radio lobes can be missed, such as the case for J1409–0302 (Speca, Hota et al. 2011). Therefore we took the NVSS data as the fundamental basis and the FIRST data were used as an auxiliary database for radio-lobe identification. The radius to search for the radio counterpart of the central optical spiral galaxy is tricky: the larger the radius is set, the more radio sources around the central galaxy one would get, and then the more time would be consumed for distinguishing the true association. Therefore a trade-off should be made on setting the

[4] https://cdsarc.cds.unistra.fr/viz-bin/cat/J/ApJS/223/20#/browse

[5] https://www.cv.nrao.edu/nvss/NVSSlist.shtml

[6] http://sundog.stsci.edu/first/catalogs/readme.html

Table 1
Parameters for 17 Spiral Galaxies that Host Double Radio Lobes

Name (1)	Ref.1 (2)	R.A. (J2000) (3)	Decl. (J2000) (4)	z (5)	S_{tot} (mJy) (6)	$P_{1.4\ GHz}$ (W Hz^{-1}) (7)	p (8)	$\log_{10} M_*$ ($M_\odot$) (9)	Environment (10)	N_{gal} (11)	Charc. (12)	Ref.2 (13)
J0209+0750	[1]	32.26979	7.83458	0.251	394	7.58×10^{25}	0.37	11.45	field	0	…	…
J0315−1906	[2]	48.96708	−19.11233	0.067	100	1.05×10^{24}	…	10.88	cluster	11	member	[2]
J0354−1340	[3, 4]	58.63688	−13.66868	0.076	15	2.05×10^{23}	…	11.13	…	…	…	…
J0806+0624	[1]	121.74358	6.41483	0.112	5	1.67×10^{23}	…	10.19	field	1	…	…
J0836+0532	[5]	129.23278	5.54502	0.099	62	1.50×10^{24}	0.23	10.91	group	4	BGG	[5]
J1328+5710	[1]	202.03879	57.17314	0.032	22	4.91×10^{22}	…	8.76	field	0	…	…
J1656+6407	[1]	254.08583	64.13136	0.212	75	9.76×10^{24}	0.91	11.50	field	5	…	…
J2318+4314	[6]	349.63650	43.24692	0.012	17	5.26×10^{21}	…	9.12	group	…	member	[6]
J2345−0449	[7]	356.38625	−4.82372	0.076	181	2.47×10^{24}	…	11.20	group	7	BGG	[13]
J1128+2417	[1, 0]	172.04848	24.29636	0.169^b	69	5.34×10^{24}	0.66	10.57	group	4	member	[0]
J1159+5820	[8, 5, 0]	179.77361	58.34330	0.054	338	2.25×10^{24}	0.85	10.88	group	1	BGG	[14]
J1352+3126	[9, 5, 0]	208.07450	31.44625	0.045	4844	2.21×10^{25}	0.98	10.91	group	1	BGG	[15]
J1409−0302	[10, 0]	212.45355	−3.04237	0.138	139	6.91×10^{24}	0.67^s	11.14	cluster	10	BCG	[15]
J1649+2635	[11, 5, 12, 0]	252.35005	26.58405	0.055	157	1.09×10^{24}	0.37^s	10.88	cluster	12	BCG	[14]
J0326−0623	[0]	51.59929	−6.38431	0.180	$6^\diamondsuit$	$4.94 \times 10^{23\diamondsuit}$	0.67	10.87	cluster	13	BCG	[16]
J1110+0321	[0]	167.60458	3.36078	0.030	587	1.17×10^{24}	0.95	9.14	group	7	member	[15]
J1134+3046	[0]	173.58466	30.77959	0.046	380	1.82×10^{24}	0.94	9.51	group	4	member	[15]

Notes. Columns (1)–(2): source name and the reference to find double lobes; Here Ref.1 is indicated by numbers: [0] = this work; [1] = Wu et al. (2022); [2] = Ledlow et al. (1998); [3] = Chen et al. (2020); [4] = Vietri et al. (2022); [5] = Singh et al. (2015); [6] = Mulcahy et al. (2016); [7] = Bagchi et al. (2014); [8] = Kozieł-Wierzbowska et al. (2012); [9] = Donzelli et al. (2007); [10] = Hota et al. (2011); [11] = Mao et al. (2015); [12] = Ortiz Martínez & Andernach (2016); Columns (3)–(5): R.A., decl. and redshift of spiral galaxies respectively. The redshift information is taken from NED (https://ned.ipac.caltech.edu) except for J0209+0750, J0806+0624, J1328+5710 and J1656+6407 which are from [1] and J1128+2417 labeled with "*b*," which is the photo-z from SDSS DR8; Column (6): total radio continuum flux density measured by the NVSS at 1.4 GHz, "◊" indicates that the flux density is uncertain due to the mixture of an unrelated source (see Section 3.1). Column (7): radio powers calculated according to Equation (1). Column (8): classification certainty taken from the "catalog.dat" of Kuminski & Shamir (2016) and the marker "*s*" indicates the classification certainty from the "spec.dat" of Kuminski & Shamir (2016); Column (9): stellar mass of the galaxy; Columns (10)–(12): environment as being a group or a cluster, the number of galaxies in the group/cluster and the character of the spiral in the environment, as being the BCG/BGG or just a member, respectively. Column (13): reference indicating spirals are in galaxy groups/clusters: [0, 2, 5, and 6] are the same as in Column (2), together with [13] = Saulder et al. (2016); [14] = Tempel et al. (2018); [15] = Tempel et al. (2012); [16] = Yang et al. (2007).

searching area to balance the time consumption. By reviewing the known cases to date (e.g., Ledlow et al. 1998; Hota et al. 2011; Bagchi et al. 2014; Mao et al. 2015; Singh et al. 2015; Mulcahy et al. 2016), we searched for the NVSS and FIRST sources within 800 kpc around the central optical spirals if the redshift information was available; otherwise a radius of 3.′5 around the spiral was set for the NVSS sources and 30″ for the FIRST sources if the redshift was unknown.

Spiral galaxies with double radio lobes may have various appearances in the radio images of NVSS and FIRST. In the low resolution image of NVSS, they could have (1) a central core with distinct double radio lobes, e.g., J1352+3126 (see Figure 4 in Singh et al. 2015); (2) unresolved central core and double radio lobes, i.e., showing a structure that is elongated, such as J1649+2635 (see Figure 5 in Singh et al. 2015); (3) distinct double-lobe structure without a core component intrinsically or extrinsically. In the high resolution image of FIRST, the spirals that host double radio lobes could show (1) a central core with distinct double radio lobes, e.g., J1649+2635 (Singh et al. 2015); (2) only a central core, because the extended lobes are resolved out by the small synthesis beam; (3) distinct double-lobe structures without a core, e.g., J1409−0302 (Hota et al. 2011). The real cases can be any reasonable combination of the above possibilities for the NVSS and FIRST data in their common surveyed area. However, such loose constraints will yield too many output images, which are very difficult to be checked manually. According to the observational fact that the associated radio lobes are generally among the closest sources to the optical center, we therefore only considered the four closest radio sources to the central galaxy for association. Unlike Ortiz Martínez & Andernach (2016) who searched for extremely symmetric and collimated jets, we allowed the angle between the two radio lobes (any pair of the four closest radio sources) to vary in the range of $180° \pm 20°$ with respect to the central galaxy. To avoid missing the cases of blended core and lobes, we also accepted the cases which have one or more radio sources close enough ($\leqslant 22.''5$, half of the beam size of the NVSS) to the central spirals. Finally, the quantity of the images that qualified for the above conditions was largely reduced and became suitable for eye inspections. About 200,000 images in total were left and inspected manually.

The probable candidates were then picked out and further examined in composite images which combined both information from radio and optical. The optical images were taken from the Dark Energy Spectroscopic Instrument (DESI) Legacy Imaging Survey[7] (Dey et al. 2019), which is deeper and has a better quality than the SDSS. More importantly, the galaxy images observed by DESI can be well modeled by "*The Tractor*" with the point-spread function considered (see Dey et al. 2019, for details). The model-subtracted image, namely, the residual image, can be conveniently used to determine the existence of spiral patterns in galaxies.

As in previous discoveries introduced in Section 1, the identified host galaxies with double radio lobes all show spiral patterns. Even for J0315−1906, which is somehow edge-on, Ledlow et al. (1998) claimed the detection of a spiral structure through a deep *B*-band exposure. We follow the same discipline in this work that a spiral pattern must be visible for the central optical galaxy. Edge-on galaxies, which appear as disks, are therefore not considered.

3. Result and Discussion

By cross-matching the spiral sample taken from Kuminski & Shamir (2016) with the radio catalogs of the NVSS (Condon et al. 1998) and FIRST (Becker et al. 1995), we successfully identify eight double-lobed spiral galaxies, three of which, J0326−0623, J1110+0321 and J1134+3046, are revealed for the first time. J1128+2417 is another case that we independently discovered in this work. However, it was recently reported by Wu et al. (2022) when we were preparing this manuscript for submission, and we have to list it as a known case. We add a note for this object in Section 3.1. Another four previously known cases: J1159+5820 (Kozieł-Wierzbowska et al. 2012), J1352+3126 (Donzelli et al. 2007), J1649+2635 (Mao et al. 2015) and Speca (J1409−0302) (Hota et al. 2011), have also been re-identified. Their recurrences validate our searching strategy. By combining the radio and optical data, we show the composite images for these eight spiral galaxies hosting double radio lobes identified in this work in Figure 1.

For the other five known cases, J0836+0532 identified by Singh et al. (2015) is included in the catalog of Kuminski & Shamir (2016), but without morphological remarks and the classification certainty is $p = 0.23$, therefore it is missed. J0315−1906 (Ledlow et al. 1998), J0354−1340 (Vietri et al. 2022) and J2318+4314 (Mulcahy et al. 2016) are not in the SDSS sky, hence we cannot get them. J2345−0449 (Bagchi et al. 2014) is not included in Kuminski & Shamir (2016). Among the 18 disk galaxies associated with double radio lobes found in Wu et al. (2022), some of the central optical galaxies seen face-on or having small inclination angles show unambiguous spiral patterns, qualifying our selection based on morphology. They belong to the same type of galaxies as discussed in this work. Except for J1128+241, which is our target J1128+2417, we examine the images and pick out seven galaxies: J0209+0750, J0219+0155, J0806+0624, J0832+1848, J1328+5710, J1656+6407 and J1721+2624 as spirals subjectively. Since J0209+0750, J0806+0624, J1328+5710 and J1656+6407 have also been claimed to show spiral features by Wu et al. (2022), so that these four common targets are included as the known cases of spirals in Table 1.

3.1. Notes on the Newly Identified Spirals with Double Radio Lobes

3.1.1. J0326−0623

J0326−0623 is a face-on galaxy at a redshift of $z = 0.18$ with two major spiral arms, clearly shown in the zoomed DESI image and the model-subtracted residual image in Figure 1. This galaxy is the brightest cluster galaxy (BCG) of a galaxy cluster in the catalog of Yang et al. (2007), which contains 13 bright member galaxies of $M_r^e \leqslant -20.5$ mag. The total flux density detected by NVSS at 1.4 GHz is about 6 mJy. However, the upper lobe is superimposed by a point-like radio source as detected by FIRST, which is associated with J032624−062212, a foreground galaxy at $z \sim 0.16$. The morphology of the radio lobes is slightly bent. It has a size of ∼430 kpc as inferred by the NVSS 5σ contour.

3.1.2. J1110+0321

J1110+0321 is a blue galaxy at $z = 0.03$. The optical observational and residual images displayed in Figure 1 indicate spiral-arm structures. This galaxy belongs to a galaxy group (Tempel et al. 2012), which contains seven members brighter than −20.5 mag. The NVSS image features an elongated morphology with two lobes close to each other, and FIRST detects bright sources at the peak in each lobe. The inner-west component detected by FIRST is probably partially associated with a background quasar QSO B1107+0337 at $z = 0.965$. The overall scale of the radio lobes measured based on the NVSS 5σ contour is about 100 kpc.

3.1.3. J1128+2417

J1128+2417 is a blue galaxy at $z = 0.169$. The optical residual image for this galaxy presents a faint imprint of spiral patterns, while the high-quality deeper image from the Hubble Space Telescope (Wu et al. 2022) clearly shows the existence of the spiral structures. With the method introduced in Section 3.3, we find this galaxy is a satellite galaxy in a galaxy group, which contains four members with $M_r^e \leqslant -20.5$ mag. The NVSS map shows unresolved radio lobes with an elongated morphology, but FIRST detects two bright jets with some bridge emission. The scale for the radio emission indicated by the NVSS is around 380 kpc.

[7] http://legacysurvey.org/

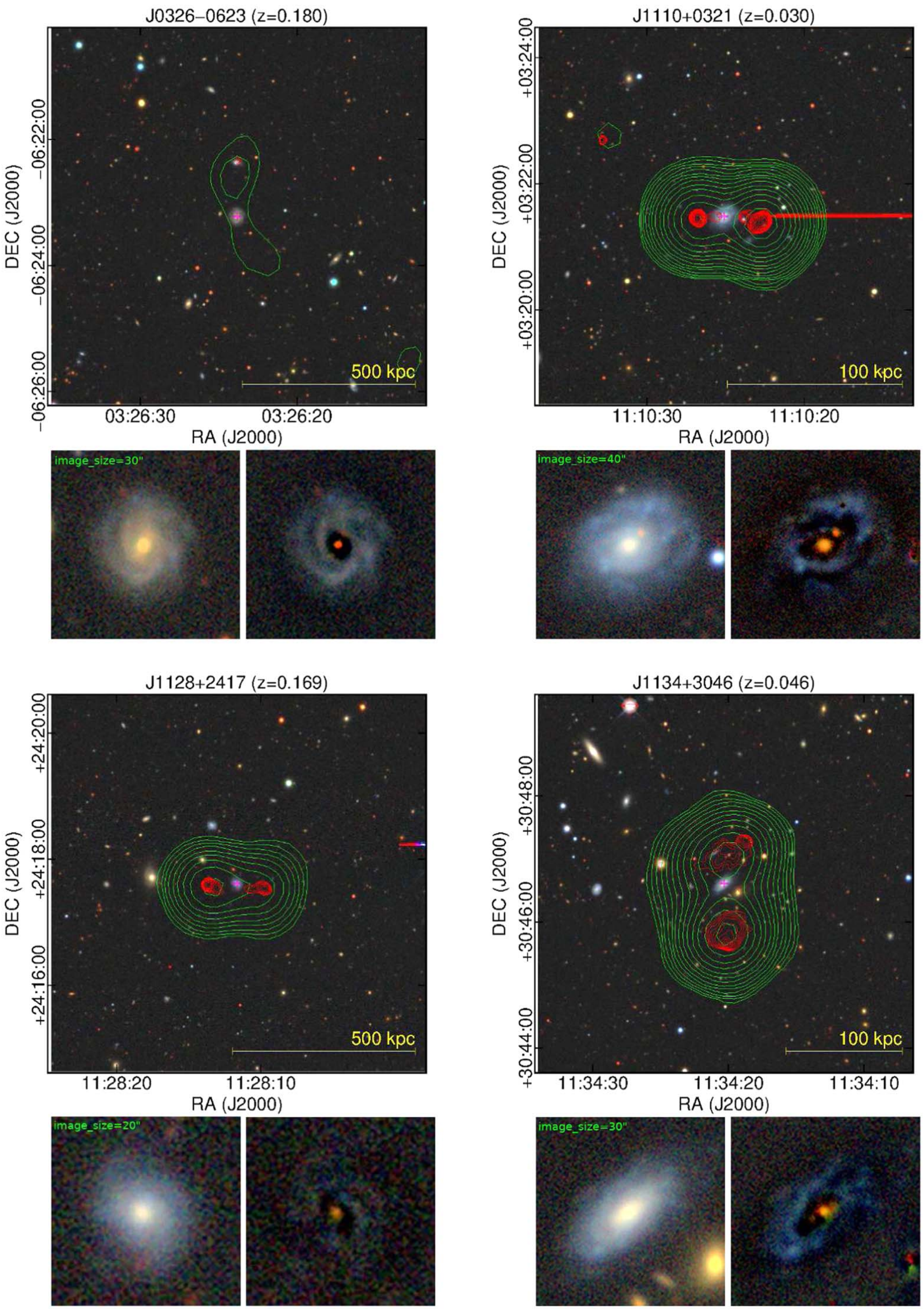

Figure 1. Images for the eight spiral galaxies hosting double radio lobes identified in this work. The panels with large figures show the optical DESI images (Dey et al. 2019) overlaid with radio contours, green for NVSS (Condon et al. 1998) and red for FIRST (Becker et al. 1995). Both the NVSS and FIRST contours satisfy $\langle S_{\rm bg}\rangle + 5 \times 2^{n/2}\sigma$ mJy beam^{-1}, here $n = 0, 1, 2, ...$ The source name and redshift are labeled on top of each plot. The cross indicates the center of the radio images. The physical scale is shown at the bottom-right corner. The panels with small figures are the zoomed-in DESI images and the model-subtracted residual images (Dey et al. 2019) for the eight spiral galaxies, with the image size marked at the top-left corner.

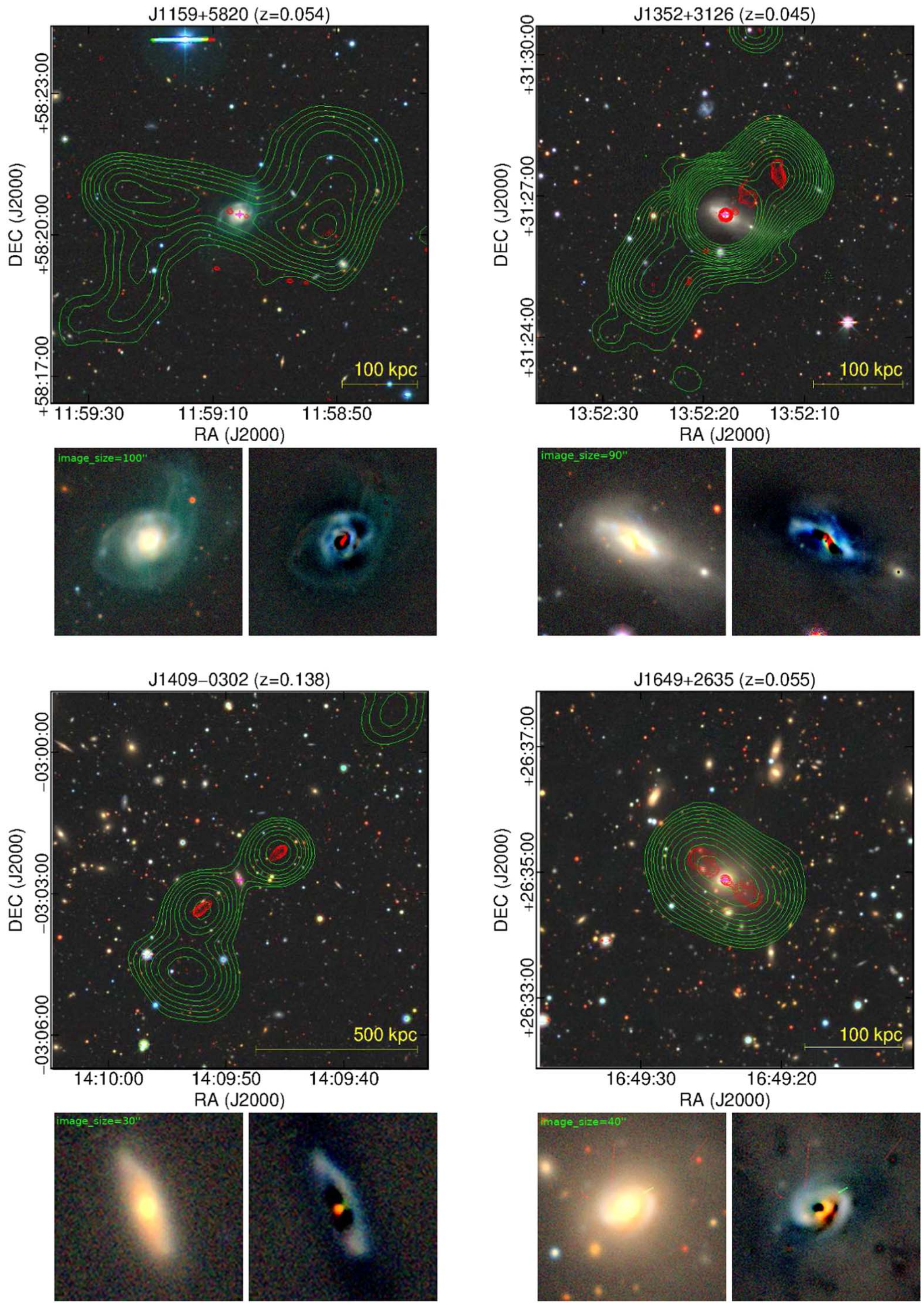

Figure 1. (Continued.)

3.1.4. J1134+3046

J1134+3046 is also a blue galaxy at $z = 0.046$. The optical residual map of this galaxy presents clear structures of spiral arms. This galaxy is a member in a galaxy group (Tempel et al. 2012), which contains four bright member galaxies with $M_r^e \leqslant -20.5$ mag. Similar to J1110+0321 and J1128+2417, the NVSS map of J1134+3046 shows unresolved radio lobes with an elongated morphology, while the FIRST image presents clear jets. The overall scale of radio emission presented by the NVSS map is approximately 190 kpc.

3.2. Relation between Radio Power and Stellar Mass of the Host Galaxy

The double radio lobes of spiral galaxies come from their central SMBH. It is therefore natural to speculate that the power of these radio lobes could be related to the mass of the SMBH. The mass of the SMBH is difficult to assess directly. However, it is related to the mass of the host galaxy (e.g., Ferrarese & Merritt 2000; Tremaine et al. 2002; Marconi & Hunt 2003). Wu et al. (2022) reported a positive correlation between $L_{1.4\,\mathrm{GHz}}$ and the masss of SMBH M_{BH} for nine previously known cases with/without their 18 new disk galaxies hosting double radio lobes (see their Figure 9). They estimated the stellar mass of the galaxy M_* by using SDSS multi-band photometry. Alternatively, the total stellar mass of the host galaxy can be well estimated based on the infrared luminosity of the galaxy which is less affected by star formation history than the corresponding optical luminosity (Bell et al. 2003; Wen et al. 2013). Wen & Han (2021) found a good scaling relation between the stellar mass of the galaxy and the 3.4 μm luminosity from the Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010). Following their procedure, we estimated the stellar mass of each galaxy listed in Table 1.

On the other hand, the 1.4 GHz flux densities for the radio lobes of all these galaxies were obtained from the NVSS catalog, and the radio powers were calculated via

$$P_{1.4\,\mathrm{GHz}} = 4\pi D_{\mathrm{L}}^2 \times S_{1.4\,\mathrm{GHz}} \times (1+z)^{1-\beta}, \qquad (1)$$

where $P_{1.4\,\mathrm{GHz}}$ is the radio power in the unit of 10^{23} W Hz^{-1} and $D_{\mathrm{L}} = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$ is the luminosity distance of a galaxy at a redshift z. $S_{1.4\,\mathrm{GHz}}$ is the 1.4 GHz total flux density of the radio lobes in mJy extracted from the NVSS catalog. $(1+z)^{(1-\beta)}$ is the k-correction term and β is the spectral index of radio galaxies. We adopted the statistical mean of $\beta = 0.74$ as obtained by Lin & Mohr (2007). All the radio flux densities and the corresponding radio powers are listed in Table 1. The radio powers are further compared with the stellar mass M_* of the 14 known (open) and three newly identified (solid) double-lobed spiral galaxies in Figure 2.

As demonstrated in Figure 2, a positive correlation exists between the stellar mass of spiral galaxy and the power of their associated double radio lobes. We test the correlation by the Spearman rank-order correlation, and get the significance $p_s = 0.00$, indicating the existence of strong dependence between M_* and radio power of the lobes, with a relation of $P_{1.4\,\mathrm{GHz}} \propto M_*^{0.8}$.

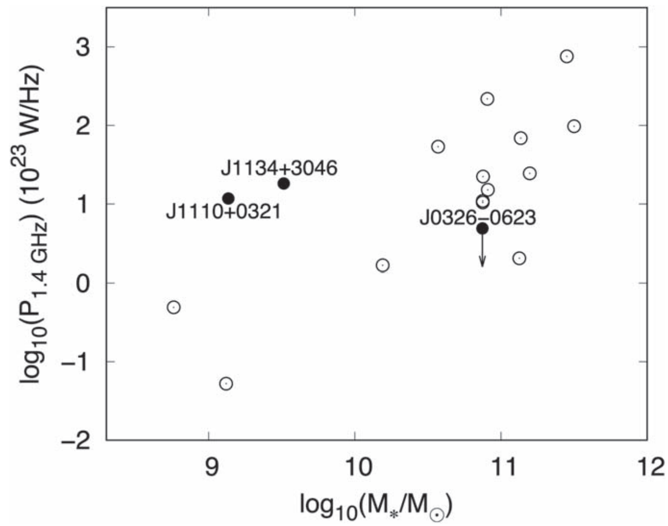

Figure 2. Radio power vs. stellar mass for 14 known (open) and three newly identified (solid, name labeled) spiral galaxies hosting double radio lobes.

3.3. Environment of the Spiral-hosted Double-lobed Sources

The mechanism for powering the large-scale double radio lobes by spiral galaxies is not clear. Physically, radio lobes may be related to a dense environment. Hota et al. (2011) pointed out that J1409−0302 belongs to a galaxy cluster of MaxBCG J212.45357−03.04237 and it is the central BCG. Its relic radio lobes may result from the accretion of galactic filaments. Based on the morphology, Singh et al. (2015) suggested a merger scenario between a spiral and an elliptical galaxy for both J1159+5820 and J1352+3126. They also noticed that J0836+0532 and J1352+3126 are in galaxy groups with very limited group members, but listed them as field galaxies together with J1159+5820. Mao et al. (2015) found that J1649+2635 is in a group rather than a cluster environment and may interact with another group, in which the bright galaxy SDSS J164933.52+265052.0 resides.

With all such accumulated samples and the new discoveries as listed in Table 1, we can have good statistics on the environment of these spiral galaxies. Based on the galaxy group/cluster catalogs (e.g., Yang et al. 2007; Tempel et al. 2012, 2018; Tully 2015), we find that most of them are located in a galaxy group or a cluster. For J0354−1340, the information is not available.

We further used the SDSS data to evaluate the richness of their parent system. We followed the procedures of Wen et al. (2012) and Wen & Han (2015) by counting the member galaxies with $M_r^e \leqslant -20.5$ mag if they have a velocity difference of 2500 km s^{-1} from the group or cluster when the spectroscopic redshift is available or have a redshift difference of $0.04(1+z)$ if only photometric redshifts are available. Here, M_r^e is evolution-corrected from M_r with $M_r^e = M_r + 1.16z$. The number of such bright member galaxies N_{gal} is listed in Table 1. We noticed that the member galaxies in the parent system of these spirals with double radio lobes are much less than those in the cluster catalog of Wen et al. (2012). Based on the numbers of member galaxies counted in the above way, we here call the system a "cluster" if ten or more members are included, or a "group" if less than 10 members are found. In addition, we found that more than half of these spirals with double radio lobes are the BCG or brightest group galaxy (BGG) in the parent system.

We pick seven spiral galaxies from Wu et al. (2022) and four of them are listed in Table 1 as known cases. We check the environment for the other three: J0219+0155, J0832+1848 and J1721+2624 following the method described above. All of them are found in galaxy groups and clusters (Yang et al. 2007; Tempel et al. 2012; Tully 2015), and are the BGGs (J0219+0155: $N_{gal} = 6$, J0832+1848: $N_{gal} = 3$) and BCG (J1721+2624, $N_{gal} = 15$). J1646+3831 is one of the six galaxies claimed to show spiral structures in Wu et al. (2022) besides J1128+2417 and the four cases. It is the BGG in a galaxy group ($N_{gal} = 5$) listed in Tempel et al. (2012). All the evidence supports that the spirals producing large-scale radio jets tend to reside in galaxy groups and poor clusters.

4. Concluding Remarks

By cross-matching a large sample of machine-selected spiral galaxies from SDSS (York et al. 2000) DR8 (Kuminski & Shamir 2016) with the full radio source catalogs of the NVSS (Condon et al. 1998) and FIRST (Becker et al. 1995), we identify three new spirals, J0326–0623, J1110+0321 and J1134+3046 hosting double radio lobes, together with five previously known double-lobed spirals.

With the largest sample of double-lobed spiral galaxies by far, we confirm that more massive spiral galaxies could produce more powerful large-scale radio jets. We notice that most spiral galaxies that host double radio lobes are located in galaxy groups or galaxy clusters and about half of them are BGGs or BCGs, implying that the formation of double radio lobes may be highly related to their surrounding environment. A more noteworthy fact is that the galaxy groups or clusters in which these spirals reside have very limited members, i.e., the environmental density is denser than the field, but not so dense and hot as in the center of rich clusters where spirals may be destroyed.

Acknowledgments

We thank the anonymous referee for helpful comments. The authors are supported by the National Natural Science Foundation of China (NSFC, Grant Nos. 11988101, 11833009), the National SKA Program of China (Grant No. 2022SKA0120103), the National Key R&D Program of China (Nos. 2021YFA1600401 and 2021YFA1600400), and the Open Project Program of the Key Laboratory of FAST, NAOC, Chinese Academy of Sciences. X.Y.G. acknowledges the financial support from the CAS-NWO cooperation program (Grant No. GJHZ1865). The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS website is www.sdss.org.

References

Bagchi, J., Vivek, M., Vikram, V., et al. 2014, ApJ, 788, 174
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, ApJS, 149, 289
Chen, S., Järvelä, E., Crepaldi, L., et al. 2020, MNRAS, 498, 1278
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693
Dey, A., Schlegel, D. J., Lang, D., et al. 2019, AJ, 157, 168
Donzelli, C. J., Chiaberge, M., Macchetto, F. D., et al. 2007, ApJ, 667, 780
Ferrarese, L., & Merritt, D. 2000, ApJL, 539, L9
Hota, A., Sirothia, S. K., Ohyama, Y., et al. 2011, MNRAS, 417, L36
Huertas-Company, M., Aguerri, J. A. L., Bernardi, M., Mei, S., & Sánchez Almeida, J. 2011, A&A, 525, A157
Keel, W. C., White, R. E., I, Owen, F. N., & Ledlow, M. J. 2006, AJ, 132, 2233
Kimball, A. E., & Ivezić, Ž. 2008, AJ, 136, 684
Kozieł-Wierzbowska, D., Jamrozy, M., Zola, S., Stachowski, G., & Kuźmicz, A. 2012, MNRAS, 422, 1546
Kuminski, E., & Shamir, L. 2016, ApJS, 223, 20
Ledlow, M. J., Owen, F. N., & Keel, W. C. 1998, ApJ, 495, 227
Ledlow, M. J., Owen, F. N., Yun, M. S., & Hill, J. M. 2001, ApJ, 552, 120
Lin, Y.-T., & Mohr, J. J. 2007, ApJS, 170, 71
Lintott, C. J., Schawinski, K., Slosar, A., et al. 2008, MNRAS, 389, 1179
Mao, M. Y., Owen, F., Duffin, R., et al. 2015, MNRAS, 446, 4176
Marconi, A., & Hunt, L. K. 2003, ApJL, 589, L21
Meert, A., Vikram, V., & Bernardi, M. 2015, MNRAS, 446, 3943
Mulcahy, D. D., Mao, M. Y., Mitsuishi, I., et al. 2016, A&A, 595, L8
Ortiz Martínez, A. F., & Andernach, H. 2016, arXiv:1610.02572
Saulder, C., van Kampen, E., Chilingarian, I. V., Mieske, S., & Zeilinger, W. W. 2016, A&A, 596, A14
Singh, V., Ishwara-Chandra, C. H., Sievers, J., et al. 2015, MNRAS, 454, 1556
Tempel, E., Kruuse, M., Kipper, R., et al. 2018, A&A, 618, A81
Tempel, E., Tago, E., & Liivamägi, L. J. 2012, A&A, 540, A106
Tremaine, S., Gebhardt, K., Bender, R., et al. 2002, ApJ, 574, 740
Tully, R. B. 2015, AJ, 149, 171
Vietri, A., Järvelä, E., Berton, M., et al. 2022, A&A, 662, A20
Wen, X.-Q., Wu, H., Zhu, Y.-N., et al. 2013, MNRAS, 433, 2946
Wen, Z. L., & Han, J. L. 2015, ApJ, 807, 178
Wen, Z. L., & Han, J. L. 2021, MNRAS, 500, 1003
Wen, Z. L., Han, J. L., & Liu, F. S. 2012, ApJS, 199, 34
Willett, K. W., Lintott, C. J., Bamford, S. P., et al. 2013, MNRAS, 435, 2835
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Wu, Z., Ho, L. C., & Zhuang, M.-Y. 2022, ApJ, 941, 95
Yang, X., Mo, H. J., van den Bosch, F. C., et al. 2007, ApJ, 671, 153
York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, AJ, 120, 1579
Yuan, Z. S., Han, J. L., & Wen, Z. L. 2016, MNRAS, 460, 3669