The characteristics of galaxies with powerful radio jets
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1 Introduction

1.1 Radio AGNs: what are they?

When gazing at the starry night sky, many are astonished by its beauty and mystery. However, few people realize that what can be seen with the naked eye is just the tip of the iceberg. It was not until the 1930s, when Karl Jansky used his horn antenna to receive signals from the sky, that people became aware of another aspect of the universe: the radio sky. It is a whole new world where our familiar constellations fade away, and countless peculiar objects reveal themselves. Many of them are known as radio jets, characterised by one or two extended, flamethrower-like structures.

In the 1950s, people for the first time recognised radio jets with two lobes in Cygnus A, a galaxy at redshift $z=0.05$. With the discovery of quasars, more and more radio jets were identified in active galactic nuclei (AGN). Studies have revealed that radio jets are highly collimated and originate from the central regions of galaxies. The radio emission from radio jets is primarily the result of synchrotron radiation, which is produced due to the movement of high-energy charged particles with relativistic velocities in magnetic fields. What’s more intriguing is that some observations of these jets indicated the presence of superluminal motion, where they appeared to travel faster than the speed of light. This is the result of relativistic beaming, when the high speed jet points towards the line of sight. These radio jets are believed to be powered by one of the most mysterious objects in the universe: supermassive black holes (SMBHs). These jetted SMBHs are what we called radio AGNs today.
Figure 1.1: A collection of radio jets in the LOFAR Two-Metre Sky Survey (Shimwell et al. 2019). The 6″ × 6″ beam is shown in the bottom left of each panel.
1.1.1 Family of radio AGNs

With the development of radio antennas and interferometers, many radio AGNs with disguising features have been identified. Based on the morphology of the jets, the radio continuum and the emission lines in the spectrum, radio AGNs can be classified into many populations as listed below.

1 FRI/FRII radio galaxies. The extended radio jets identified in radio AGNs can typically be separated into two types based on the brightness profile of the jets. Fanaroff & Riley (1974) found most radio galaxies have radio jets that are either core-brightened or edge-brightened, which are then known as FRI and FRII radio galaxies, respectively. These two types of radio galaxies are different not only in the structure of jets but also in the radio loudness, i.e., the radio luminosity with respect to the optical luminosity, with FRII radio galaxies tend to be more radio loud. Besides these two common FR types, recent studies also suggested FR0 type radio galaxies, which are similar to the FRI but lack extended emission and are more compact. Moreover, there are also some radio galaxies with more complicated radio structures such as X-shape and Z-shape jets, which cannot be classified into FR types.

2 Flat and steep spectrum radio AGNs. The radio continuum spectrum of radio sources is usually fitted with a powerlaw spectrum where the flux density $S_\nu \propto \nu^{-\alpha}$. The spectral indices $\alpha$ also divide the radio AGNs into two populations: steep spectrum sources with $\alpha > 0.5$ and flat spectrum sources with $\alpha \leq 0.5$. While normally radio AGNs have an $\alpha$ of about 0.7, the flat spectrum sources are namely blazars, which include two subclasses, flat spectrum radio galaxies and BL Lac objects, depending on the presence of broad emission lines in their optical spectrum. These flat spectrum sources are radio AGNs with jets pointing close to the line-of-sight (LOS). More detailed spectrum energy distribution (SED) studies show that some radio sources have a spectrum with a peak at frequencies from $< 1$GHz to $> 5$GHz. These are namely peaked spectrum sources. They are likely to be young and small radio jets and the peaks are due to synchrotron self-absorption or free-free absorption.
3 HERGs/LERGs. A more important dichotomy for radio AGNs is based on the presence of high excitation lines in their optical spectra. The radio galaxies with strong emission lines are high-excitation radio galaxies (HERGs) while those without are low-excitation radio galaxies (LERGs). More specifically, these two types of galaxies can be distinguished by the equivalent width of [O III] or their positions in the BPT diagrams. It is widely accepted that these two types of radio galaxies are fundamentally different as they show significant discrepancies in star formation rate, stellar mass and the SMBH accretion rate. Whereas HERGs are usually blue gas-rich low-mass galaxies and have high Eddington-scale accretion rate\(^1\) (>0.01), LERGs are usually red massive early-type galaxies and have a low Eddington-scale accretion rate (<0.01). Theoretically, they correspond to different accretion scenarios. HERGs, with a high accretion rate, are thought to have a geometrically thin, optically thick accretion disc, while LERGs are geometrically thick, advection-dominated accretion flow (ADAF) systems. Based on the different accretion scenarios, the dichotomy can be extended to non-radio-selected AGNs. The Seyferts and quasars are referred to as HERGs, and the low-ionisation narrow emission line regions (LINERs) are referred to as LERGs. Furthermore, ADAF systems tend to be more efficient in jet launching, whereas the fraction of radio-loud systems in high-excitation AGNs is generally lower than that in low-excitation AGNs.

The various types of radio AGNs form a big family. The intrinsic differences in these types can be the different viewing angles, obscurations and accretion rates as shown in Table 1.1. More detailed discussions could be found in the review works of Heckman & Best (2014) and Hardcastle & Croston (2020).

1.1.2 Radio AGNs in galaxies

The presence of a radio AGN is not common in galaxies, and recent studies showed that the overall fraction of radio AGNs in nearby galaxies is less than 10% (Best et al. 2005a; Sabater et al. 2019). However, the fraction of radio AGNs increases rapidly with the stellar mass \(M_\star\) of galaxies.
Table 1.1: A unified model for radio-loud AGNs. Adapted from [Hardcastle & Croston (2020)].

<table>
<thead>
<tr>
<th>Low excitation</th>
<th>High excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet at large angles to line of sight</td>
<td>Jet closely aligned to line of sight</td>
</tr>
<tr>
<td>LERGs (FRI or FRII)</td>
<td>BL Lac</td>
</tr>
<tr>
<td>Intermediate angles</td>
<td>Broad-line radio galaxy, BLRG, or lobe-dominated or steep-spectrum quasar (some FRI, mostly FRII)</td>
</tr>
<tr>
<td>Low excitation</td>
<td>High excitation</td>
</tr>
<tr>
<td>Narrow-line radio galaxy (NLRG, some FRI, mostly FRII)</td>
<td>Core-dominated, flat-spectrum or OVV quasar</td>
</tr>
</tbody>
</table>

galaxies. [Sabater et al. (2019)] indicated that all the massive galaxies above $M_\star = 10^{11} M_\odot$ host a radio AGN with luminosity $L_{150\text{MHz}} > 10^{21}$ W Hz$^{-1}$. These radio jets with massive energy output are thought to influence the evolution of these massive galaxies significantly ([Fabian 2012]).

An important problem in the studies of galaxy evolution is to explain the low star formation rate in massive galaxies. In the absence of an effective heating mechanism, the intergalactic materials (IGMs) around a massive galaxy are predicted to form a cooling flow into the galaxy and maintain the star formation ([Fabian et al. 1994]). However, the observed cooling flow and the star formation rate in massive galaxies are greatly below the prediction ([Peterson et al. 2001, 2003; Tamura et al. 2001]). This is also reflected in the discrepancies between the observed and simulated galaxy stellar mass functions, with the observed number of massive galaxies much lower than the prediction from the dark matter mass function (e.g. [Shankar et al. 2006; Driver et al. 2009]). The deficit of massive galaxies is usually attributed to the feedback of AGNs ([Silk & Rees 1998; Granato et al. 2004]).

The feedback from radio AGNs is mainly in the form of the interaction between radio jets and nearby gas. Radio jets are high-speed charged particle flows that originate from SMBHs and contain enormous amount of kinetic energy. As the jets interact with IGM, they would be decelerated...
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and part of the kinetic energy would be converted to thermal energy in IGM (Tucker & David, 1997, Soker et al., 2001). In this way, the gas is heated and the formation of cooling flow is suppressed, hence the galaxy does not have enough cold gas to form stars. This interaction between radio jets and IGMs could be found in the X-ray images of galaxy clusters and groups containing bright radio galaxies in the form of cavities or bubbles blown up by jets (Bohringer et al., 1993a, Carilli et al., 1994, Fabian et al., 2000, 2002, Schmidt et al., 2002, McNamara et al., 2000, Birzan et al., 2004). A key question for this scenario is whether the energy injected by radio AGNs is enough to balance the cooling of the IGM and keep the galaxy red and dead.

To answer this question, it is necessary to compare the average injected energy from jets and the energy loss in the cooling process. Birzan et al. (2004) estimated the $pV$ energy of the X-ray cavities of a sample of galaxy clusters using the Chandra X-ray images. They found that the mechanical power associated with the cavities is related to the radio luminosity of the central galaxies. This relation was confirmed and refined in many later studies (e.g. Dunn et al., 2005, Birzan et al., 2008, Cavagnolo et al., 2010). Thus the radio luminosity can be used to estimate the jet’s mechanical power in large samples. The average mechanical power output of radio AGNs can then be estimated by the radio luminosity and the fraction of radio AGNs in galaxies, which represents the duty cycle of radio AGNs, i.e. the fraction of time that a powerful radio jet is in place in the history of the galaxy. This can be compared with the gas cooling rate in massive galaxies, which is usually estimated through measurements of the X-ray luminosity. With large radio surveys such the National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS, Condon et al., 1998), the Faint Images of the Radio Sky at Twenty centimetres (FIRST, Becker et al., 1995) survey and the LOw Frequency ARray (LOFAR, van Haarlem et al., 2013) Two-metre Sky Survey (LoTSS, Shimwell et al., 2019), it was confirmed that the time-average jet mechanical power can balance or even offset the energy loss in the cooling of gas in massive galaxies (Best et al., 2005b, 2006, Sabater et al., 2019).

Previous studies have shown the importance of radio jets in the galaxy’s evolutionary history. However, to fully understand the AGN-galaxy co-evolution, we also need to know how jets are triggered, which is a very basic question not yet been fully answered. Only when the mechanism and condition for jet launching are revealed can we understand the time
1.2 Jet launching mechanisms

Radio jets release a massive amount of energy and the speed of the jet material can be close to the speed of light, therefore it is crucial to know the physical mechanism that can produce a jet. Theoretically, two jet launching mechanisms are most widely accepted and discussed, the Blandford-Znajek (BZ, Blandford & Znajek 1977) mechanism and the Blandford-Payne (BP, Blandford & Payne 1982) mechanism.
In the BZ mechanism, a collimated jet is produced in a fast rotating Kerr black hole with large scale magnetic field around it. The magnetic field threading the horizon of the black hole would be torqued as the black hole rotates. This results in the deceleration of the black hole spin and the rotational energy would be extracted in the form of Poynting flux and produce a relativistic jet. In this mechanism, the key parameters that determine the jet production are the black hole spin, the magnetic field, the accretion rate and the mass of the central black hole. Based on the BZ mechanism, many studies proposed that the spin of a black hole determines the radio-loudness of an AGN (e.g. Wilson & Colbert 1995; Hughes & Blandford 2003), which is referred to as the spin paradigm. A correlation between the jet power and the black hole spin has been found in some stellar mass black holes and blazars (Narayan & McClintock 2012; Chen et al. 2021a).

The other mechanism, the BP mechanism, suggests that magnetic fields anchored at the accretion disk may also produce high speed jet or outflow. Unlike the BZ mechanism where the jet kinetic energy is converted from the rotational energy of the black hole, the BP jet takes the rotational energy in the accretion disk. This process also provides a plausible way to remove the angular momentum from the accretion disk and cause the accreted materials to move inwards. In this mechanism, the jet power would be related to the disk luminosity, which was confirmed in many studies (e.g. Rawlings & Saunders 1991; Sbarrato et al. 2014; Mukherjee et al. 2019).

In practice, it is difficult to constrain the jet launching mechanism directly because of the limitation of instrumental resolution. One of the most important ingredients, the black hole spin, is especially hard to constrain.

The black hole spin measurements are mainly based on the X-ray reflection spectrum. The X-ray emission, which originates from the hot corona above the accretion disk (Fabian et al. 2015), would excite the atoms at the surface of the accretion disk and produce fluorescent emission lines. These reflecting lines would be significantly broadened and asymmetric because of the Doppler effect and Relativity effect (Fabian et al. 1989). As these effects are related to the innermost stable circular orbit (ISCO), at which the orbital motion of the accreting gas becomes unstable because of relativistic effects, and the ISCO is smaller in black holes with higher spin, the reflecting lines can therefore be used to estimate the black hole spin. However, the signatures are subtle and can be misinterpreted especially
when strong disk winds are present (Reynolds 2012). Therefore, only a small number of black holes have reliable spin measurements so far, and they are all high spin systems (Reynolds 2019). Interestingly, current spin measurements suggested a possible decreasing trend with stellar mass, especially for galaxies above $\sim 10^8 M_\odot$. This seems to be in conflict with the trend that more massive galaxies have a higher fraction of radio AGNs. High sensitivity and spectral resolution X-ray telescopes in the future, for example, the Athena (the Advanced Telescopy for High-ENergy Astrophysics), will be needed to reduce the bias in black hole spin studies and verify the jet launching mechanism.

Given the difficulties of the direct measurement of black hole spins and magnetic fields, these measurements are only feasible in a small number of nearby radio AGNs with high luminosity. With the development of new generation radio telescopes and interferometers such as the LOFAR and the Square Kilometre Array (SKA), a large number of radio AGNs with different morphology and power will be observed. This enables us to study the jet launching mechanism statistically with indirect methods.

### 1.3 Linking jets to the evolutionary path of galaxies

The jet launching problem can be understood by studying the conditions needed to trigger the activity of radio AGNs. The dependence of radio jets on the accretion rate, black hole spin or magnetic field could be encoded in the correlations between radio AGNs and their host galaxies. This would also provide information about the AGN-galaxy coevolution. This section discusses the relation between radio AGNs and the evolutionary path of their galaxies, which may imprint the requirement to trigger the radio jets.

#### 1.3.1 Radio AGNs in galaxies with different morphology: observations

Early in the 1970s, people found that radio AGNs are predominantly hosted by elliptical galaxies (Condon & Dressel 1978; Balick & Heckman 1982; Smith et al. 1986). This may not be surprising given the radio AGNs-stellar mass relation and the trend that massive galaxies tend to be elliptical. However, the morphology preference of radio AGNs remains even if the stellar mass is fixed. Barišić et al. (2019) used the radio AGNs in the NVSS and the FIRST survey to study the projected axis ratio of the host galaxies with the Sloan Digital Sky Survey (SDSS; York et al. 2000). In their sample
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Figure 1.3: A schematic diagram showing the possible link between radio AGNs and the morphology of host galaxies.

with radio luminosity $L_{1.4\,\text{GHz}} > 10^{23}\,\text{W}\,\text{Hz}^{-1}$, the fraction of radio AGNs in passive galaxies at fixed stellar mass increases with optical axis ratio, i.e. round galaxies are more likely to be radio-loud than elongated galaxies. This trend was interpreted as the result of the spin paradigm and the different merger histories of the galaxies (Fig. 1.3). While round galaxies are more likely to have an active merger history, the merging of SMBHs followed by the galaxy mergers might also cause larger spin parameters, in contrast to the elongated galaxies which are less affected by mergers.

The link between mergers and radio AGNs was also implied in studies of the light profiles of galaxies. Capetti & Balmaverde (2007) investigated the Hubble Space Telescope (HST) images of nearby radio-loud and radio-quiet AGNs. They analysed the light profile of the host galaxies and found the radio-loud AGNs are hosted by core galaxies, which show central light deficit with respect to a Sérsic profile, while radio-quiet AGNs are hosted
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by galaxies without signs of a core structure. Wang et al. (2016, 2019) also investigated the r-band images of a sample of nearby \((z < 0.05)\) radio-selected Seyfert 2 galaxies in the SDSS and performed bulge-disk decompositions. They found radio-loud AGNs with larger black hole masses have a preference for being in classical bulges. As the core structure and classical bulges are both signatures of past mergers in the formation history of galaxies, this research also indicates that the triggering of radio jets is related to galaxy mergers.

In addition, deep optical images of radio galaxies are more likely to show signatures of past merger events than radio-quiet galaxies (Heckman et al. 1986; Smith & Heckman 1989). Pierce et al. (2019) used deep imaging data for 30 intermediate power local HERGs \((22.5 < \log L_{1.4\text{GHz}} \text{ (W Hz}^{-1}) < 24)\) to study the morphology of radio galaxies. The fraction of galaxies with disturbed signatures, which are usually associated with mergers or interactions between galaxies, decreases with radio power.

These results all indicate that powerful radio galaxies have a merger dominated evolutionary path while less powerful radio galaxies may not relate to mergers. The possible influence of mergers could be on the spin of central SMBHs or on the fueling of the activity. As the LoTSS data provided a large number of radio AGNs with lower radio luminosities, this correlation between radio AGNs and mergers can be tested further.

1.3.2 Evolutionary path of massive galaxies

A key to studying the link between radio AGNs and the evolutionary path of galaxies is to choose a proper indicator of the evolutionary history. It would be important to have basic knowledge about the evolution of massive early-type galaxies (ETG). For the massive galaxies, there could be two distinct evolution channels, corresponding to a dichotomy between two types of ETGs based on the observations of morphology and kinematics of galaxies (see Chang et al. 2013; Cappellari 2016, and reference therein).

One type of ETGs is the slow rotator. Early long-slit spectroscopic studies revealed that some ETGs have much lower orbital velocity than the local velocity dispersion in the galaxy, indicating a low angular momentum in these galaxies (Illingworth 1977). These galaxies are triaxial systems and exhibit boxy isophotes (Binney 1978; Bender et al. 1988). The light profile of the slow rotators tends to show cores (Emsellem et al. 2011). As integral-field spectroscopy (IFS) methods became available, more details of ETGs have been studied in IFS surveys such as the Spectroscopic Areal Unit for
Research on Optical Nebulae (SAURON) survey (de Zeeuw et al. 2002), the ATLAS3D (Cappellari et al. 2011a), the Calar ALto Legacy Integral Field Area survey (CALIFA; Sánchez et al. 2012) and the Mapping Nearby Galaxies at Apache Point Observatory survey (MaNGA; Bundy et al. 2015). IFS studies suggested that slow rotators have a low angular momentum and weak or no disc component in the velocity maps (Emsellem et al. 2011, Cappellari 2016). The slow rotators are believed to be associated with a dry major merger dominated evolution, so that the stellar disc component in the structure would be destroyed.

The other type is the fast rotator. The fast rotators show ordered rotation in the velocity maps similar to spiral galaxies, hence they tend to have a large angular momentum (Emsellem et al. 2007, 2011, Cappellari et al. 2007). They are more likely to be disc-like and show no core structure. In contrast to the slow rotators, fast rotators could be galaxies that evolved mainly through secular processes (gas accretion, bulge growth and quenching), and the stellar discs would not be destroyed in this way (Cappellari 2016).

In summary, studying the evolutionary path is basically related to the classification of fast/slow rotators. In a large sample, this can be studied with the distribution of axis ratios (Chang et al. 2013, Barišić et al. 2019). Studies based on isophotes or the decomposition of light profiles can also provide good constraints. With the IFS observations, the angular momentum can be estimated, which can provide more precise classifications.

1.4 This thesis

Previous sections have illustrated the importance of radio AGNs studies. As the main character in radio sky, radio AGNs exhibit various features and populations. They are believed to be responsible for the lack of star formation in massive galaxies. However, it is still unclear how and when these radio AGNs become active and influence the host galaxies. This became one of the fundamental questions to be addressed in the field of radio AGNs. A possible scenario is that the post-merger galaxies would have a merged SMBH with a different spin with respect to the mergerless galaxies, thus having a higher probability to trigger radio jets. This thesis discusses such a scenario mainly based on the LoTSS data combined with optical/infrared information. This thesis includes statistical studies
on the host galaxy morphology, kinematics and jet-galaxy alignment of radio AGNs and aims to answer the following questions: how are radio AGNs triggered?; how does the morphology of radio galaxies change with radio power?; can the heating of jets balance the cooling of gas in elongated galaxies?; are jets aligned with the minor axis of host galaxies and would this change with luminosity?

1.4.1 Data used in this thesis

To study the correlation between radio AGN and host galaxies, we used large sky surveys in radio and optical/infrared bands. The surveys used in this thesis are listed below.

- **Radio surveys**
  - LoTSS: The LOFAR Two-metre Sky Survey (LoTSS; Shimwell et al. 2017) is a high-resolution low-frequency (120 to 168 MHz) survey aiming to cover the whole northern hemisphere using LOFAR. LOFAR is a pan-European radio interferometer with longest baselines of $\sim 1500$ km. LOFAR achieves an unprecedented sensitivity, resolution and survey speed at frequencies from 10 to 200 MHz. The first data release of LoTSS (LoTSS DR1; Shimwell et al. 2019) covers a region of 424 square degrees centred on the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX; Hill et al. 2008) Spring Field with a median rms of $S_{144 \text{ MHz}} = 71 \mu \text{Jy beam}^{-1}$ and a resolution of 6$''$. Over 300,000 sources are detected in DR1. The second data release of LoTSS (LoTSS DR2; Shimwell et al. 2022) covers two contiguous regions centred at RA $\sim 13h$ and RA $\sim 1h$ respectively. The total area of coverage is 5634 square degrees, which is about 27% of the entire north sky. The LoTSS DR2 has an rms noise level of 83 $\mu \text{Jy beam}^{-1}$ and a resolution of 6$''$, and contains 4,396,228 radio sources. The point-source completeness of this survey was about 90% at a peak brightness of 0.8 mJy beam$^{-1}$ and the positional accuracy was about 0.2$''$.

  - NVSS and FIRST: The National Radiio Astronomy Observatory (NRAO) Very Large Array Sky Survey (NVSS; Condon et al. 1998) and the Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey (Becker et al. 1995) are two surveys at
1.4 GHz using the Karl G. Jansky Very Large Array (VLA). The NVSS observed the entire sky north of \(-40^\circ\) declination with a resolution of 45\". At this low resolution, this survey captures the entire radio emission of most radio sources and therefore can be used to constrain the total flux of radio sources. The NVSS detected sources with a flux density above 2.5 mJy. In contrast, the FIRST survey has a higher resolution of 5\". It was designed to cover \(\sim10000\) square degrees of the region that would be observed by the Sloan Digital Sky Survey (York et al. 2000) and contains \(\sim946\ 000\) sources with a median rms of 52 \(\mu\)Jy beam\(^{-1}\). The high resolution of the FIRST survey enables studies on the structure of radio sources and reliable cross-matching with optical surveys. The two surveys can be combined into an NVSS-FIRST dataset based on the methods described in Best et al. (2005b) to study nearby galaxies.

**VLA-COSMOS 3 GHz Large Project:** The Karl G. Jansky Very Large Array Cosmic Evolution Survey (VLA-COSMOS) 3 GHz project (Smolčić et al. 2017a) covers an area of \(\sim2.6\) square degrees, enclosing the 2 square degree COSMOS field with 384 hours of observations, and reaches a mean rms of \(\sim2.3\) \(\mu\)Jy beam\(^{-1}\) and a resolution of 0.75\". The source catalogue of the VLA-COSMOS 3 GHz survey contains 10830 radio sources above 5\(\sigma\) with an astrometric accuracy of about 0.01\" at the bright end (Smolčić et al. 2017a). The rich multiwavelength information in the COSMOS field helps in the identification of radio AGN and determining their properties. Because high resolution optical images from the Hubble Space Telescope observation are available in the COSMOS field, the VLA-COSMOS 3 GHz data can be used to study the morphology of radio AGNs at redshifts up to 1.

**Optical surveys**

- **SDSS:** The Sloan Digital Sky Survey (SDSS; York et al. 2000) is an imaging and spectroscopic survey mapping one-quarter of the sky to a depth of \(g' \sim 23\) mag with the Sloan Foundation 2.5 m telescope at the Apache Point Observatory (APO). The SDSS detected over 350 million objects in \(ugriz\) bands and made spectra for over 900 000 galaxies (Abazajian et al. 2009). This survey
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has been widely used by astronomers and contains important information for the objects (e.g. redshift, morphology, stellar mass, and star formation rate).

– **MaNGA**: The Mapping Nearby Galaxies at APO (MaNGA; Bundy et al. 2015) survey is a part of the fourth generation of the SDSS. The MaNGA survey uses the integral field units (IFUs) equipped by the Baryon Oscillation Spectroscopic Survey (BOSS) spectrographs on the 2.5-metre Sloan Telescope (Smee et al. 2013). These IFUs have 19 to 127 hexagonally bundled 2″ fibres corresponding to diameters of 12″ to 32″. The final spectra provided by MaNGA covers wavelengths from 360 to 1000 nm, with a resolution of $R \sim 2000$ (Law et al. 2016). The MaNGA aims to observed $\sim 10,000$ nearby galaxies with a signal-to-noise ratio of 4–8 at 23 AB mag arcsec$^{-2}$ in r band. These galaxies are selected to have a flat number density distribution in the i-band absolute magnitude within $0.01 < z < 0.15$ (Wake et al. 2017). This selection strategy ensures that the galaxy sample has a flat stellar mass distribution between $10^9 - 10^{12} M_\odot$. Galaxies in the primary and secondary samples of MaNGA are mapped by IFUs out to 1.5 and 2.5 effective radii ($R_e$), respectively. The MaNGA data can be used to study the kinematics and structures of galaxies hosting radio AGNs in this thesis.

– **The DESI Legacy Surveys**: The Dark Energy Spectroscopic Instrument (DESI) Legacy Imaging Surveys (hereafter the Legacy Surveys; Dey et al. 2019) consist of three public projects, the Dark Energy Camera Legacy Survey, the Beijing-Arizona Sky Survey and the Mayall z-band Legacy Survey, using three telescopes: the Blanco telescope at the Cerro Tololo Inter-American Observatory; the Mayall Telescope at the Kitt Peak National Observatory; and the University of Arizona Steward Observatory 2.3 m (90 inches) Bart Bok Telescope at Kitt Peak National Observatory. A total of 14,000 square degrees of extragalactic sky in the northern hemisphere was observed in the grz bands to uniform depths (\(\sim 23\) AB magnitude at $r$ band). The point-spread functions (PSFs) in the Legacy Survey have a median full width at half maximum (FWHM) of about $1''$, comparable to that for the SDSS images (York et al. 2000). The software
package Tractor \cite{Lang2016} was used to extract sources from the stack images and construct the source catalogue with morphological information, including the shapes and profiles of the galaxies. The Legacy surveys are used in the LoTSS DR2 to find the optical counterparts of radio sources (Hardcastle et al. in prep.).

1.4.2 Thesis structure

The thesis is structured as follows.

Chapter 2: This chapter presents a study based on the LoTSS DR1. This work investigated the prevalence of radio AGNs in \( \sim 15000 \) local (\( z < 0.3 \)) passive galaxies in the SDSS data release 7 (DR7) and its dependence on the axis ratio of galaxies. With the high sensitivity of LoTSS, the work included low luminosity radio AGNs down to \( L_{150\,\text{MHz}} = 10^{21}\,\text{W Hz}^{-1} \). The optical morphology of the host galaxies of radio AGNs with different stellar masses, radio luminosities and environments were considered. We found that the low luminosity radio AGNs (\( L_{150\,\text{MHz}} < 10^{23}\,\text{W Hz}^{-1} \)) do not have a preference for the galaxies’ shape, while higher luminosity radio AGNs are more likely be in round galaxies at fixed stellar mass. This result is in line with \cite{Pierce2019, Wang2019}. We suggested that the results implied different evolutionary paths for the host galaxies of high- and low-power radio jets.

Chapter 3: This chapter extends the study in Chapter 2 to higher redshifts (\( z < 1 \)). We used the radio AGN sample based on the VLA Cosmic Evolution Survey (VLA-COSMOS) 3GHz Large project \cite{Smolcic2017} and the shape measurement results based on the high resolution images of the HST. Compared to the results based on the LoTSS DR1, the radio power dependence of the project axis ratio distributions of radio AGNs seemed to become less significant at higher redshift. The high-power radio AGNs seemed not to prefer round galaxies as their counterparts in low redshifts. This could be due to the higher density in a higher redshift universe, which might lead to a higher average luminosity of AGNs.

Chapter 4: To further investigated the intrinsic structures of the host galaxies of radio AGNs, this chapter presents for the first time the relation between the radio AGNs and the kinematics of the host galaxies. In the LoTSS data release two (DR2; Shimwell et al. 2022) and the NVSS-FIRST data \cite{Best2012}, we selected 349 nearby radio AGNs with
reliable kinematical measurements in the MaNGA survey. We studied the prevalence of radio AGNs in galaxies with different ellipticities and angular momentums, which also indicate the rotator type of the galaxies. The trend that slow rotators tend to have a higher fraction of radio AGNs than fast rotators was confirmed in this chapter. The chapter also shows that the radio AGN fraction-axis ratio relation revealed in previous works could be reproduced based on the radio AGN fraction-angular momentum relation. As the angular momentum of galaxies is a better proxy of the galaxy’s evolutionary path, the reproduction result confirmed that the radio AGN-axis ratio relation is the result of the evolutionary path dependence of the radio AGNs.

**Chapter 5:** Aside from the signatures in the morphology and kinematics of host galaxies, the direction of the jet with respect to the galaxy also imprints the importance of black hole mergers in the growth of SMBHs and provides information more closely related to the SMBHs. This chapter presents the jet-galaxy alignment using data from the LoTSS DR2 and the Dark Energy Spectroscopic Instrument (DESI) Legacy Imaging Surveys (hereafter the Legacy Surveys). The work analysed the reliability of the position angle (PA) measurements in the radio and optical images, taking into account the bias and uncertainties in the measurements. The final radio AGNs sample contains 5350 sources with reliable optical PA (OPA) and radio PA (RPA) measurements. This work showed the distributions of the difference between OPA and RPA (dPA) for radio AGNs with different stellar mass, radio luminosity and axis ratios. With some simple assumptions, the work tried to find the intrinsic jet-galaxy alignment distributions for different radio AGNs based on the dPA distributions. We showed that the models could fit the observation dPA distributions well and lower luminosity samples have significantly more minor axis alignment jets. This supports the previous results showing low luminosity radio AGNs are less affected by mergers.

### 1.5 Future prospect

The works presented in this thesis are all related to a key question: what determines the activity of an AGN? Based on previous works, regarding the radio AGNs, the relation between the radio power and the galaxy morphology implies links between radio AGNs and the evolutionary path of galaxies. But we still do not know exactly how the evolutionary path of
galaxies affects the key ingredients of the jet launching mechanism such as the spin, the accretion rate and the magnetic field. Research in the coming years will focus on these topics.

To address this main question, there could be many different approaches based on the huge amount of data from the big science projects in the coming years. Regarding the radio observation, the development of LOFAR2.0 and SKA will achieve higher sensitivity, higher resolution and faster data processing. This will generate a larger and better RLAGN sample than ever before, and extend our vision to a fainter and further universe. We will then be able to have a deeper understanding of the whole RLAGN population. In the meantime, the host galaxies properties, e.g. stellar mass, star formation rate and morphology, will be investigated with unprecedented detail by not only the existing surveys but also the upcoming projects based on new instruments such as WEAVE (Dalton et al. 2012), Euclid (Laureijs et al. 2011), LSST (Ivezić et al. 2019), CSST (Yuan et al. 2021). These will provide enormous data allowing a thorough study of galaxies with both photometric and spectroscopic, spatial-resolved and time-resolved methods. These should help us better understand the fuelling and feedback processes of AGNs and their role in the galaxy-forming history. High-quality X-ray data from XMM-Newton (Jansen et al. 2001), eROSITA (Merloni et al. 2012) and eXTP (Zhang et al. 2016) will be used to study the spectrum, polarization and variability of AGNs, so as to constrain their detailed structure and spin. Combining the information from different bands and methods, we should be able to better understand how AGNs are triggered and how they are connected with host galaxy star-forming.