EXPLORING EXTENDED RADIO GALAXIES WITH LOFAR

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Abstract

Extended radio sources are an important minority population in modern, deep radio surveys because they enable detailed investigation of the physics governing radio-emitting regions such as active galaxies and their environments. The Low-frequency array (LOFAR) Two-metre Sky Survey (LoTSS), at 150 MHz, is the largest radio survey to date in terms of numbers of sources and data volume, and is sensitive to both compact and extended emission, making it ideal for the study of extended radio sources.

Cross-identification of radio sources with optical host galaxies is challenging for this extended population, due to their morphological complexity. In LoTSS Data Release 1 an automated statistical identification process for compact sources was supplemented by a citizen science identification process. I present a novel method for automating the host identification of extended sources by using ridgelines, which trace the assumed direction of fluid flow through the points of highest flux density. Applying my code, RL-XID, I demonstrate that ridgelines are versatile; they can be used both for optical host identification and morphological studies. RL-XID draws ridgelines for 85% of sources brighter than 10 mJy and larger than 15 arcsec, with an improved performance of 96% for the subset >30 mJy and >60 arcsec. I demonstrate that RL-XID successfully identifies the host for 98% of the sources with successfully drawn ridgelines, and performs at a comparable level to visual identification via citizen science.

Exploring galaxy populations helps us to understand their evolution and build better population models. I present new VLA observations that reveal the structure of a population of low-luminosity FRII radio galaxies discovered in LoTSS. Fanaroff and Riley (1974) identified a relationship between luminosity and radio structure, with FRIs having low-luminosity, centre bright jets and FRIIs having higher luminosity, edge-brightened jets. Using LoTSS, Mingo et al (2019) demonstrated an overlap in luminosity between FRI/FRII morphology, discovering a sub-sample of FRIIs with luminosities up to three magnitudes lower than the typical FR break. To continue to apply the traditional FR classifications in upcoming surveys we need to understand the structure and dynamics of the low-luminosity FRII population. The VLA observations I present in this thesis are a sample of LoTSS-selected low-luminosity FRIIs which allow me to make comparisons between the two FRII luminosity populations. I found systematic differences in the prevalence of compact features, with a higher fraction of cores in the low luminosity sample, and a higher fraction of hotspots in the high luminosity sources. I have also identified six new remnant candidates and three new restarting candidate sources.
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"Long days and pleasant nights."

Mid-World Greeting,
Stephen King, The Dark Tower

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“For the last five years I’ve been trying to do one thing, get to right here.”

Natasha Romanoff,
Marvel’s, Avengers: Endgame
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1 INTRODUCTION

“Before we get started, does anyone want to get out?”

Steve Rogers,
Marvel’s, Captain America: The Winter Soldier

A small percentage of galaxies are classed as active galaxies, and a further sub-group of these are radio galaxies. Here the accretion of the surrounding gas onto the central supermassive black hole produces relativistic jets, which emit radio emission that can extend to megaparsecs beyond the host galaxy. This energetic input from radio galaxies can have an impact on the galaxies they inhabit, and on the large-scale environment. The most direct effect they have on their surroundings is through the transfer of energy from jets and large-scale outflows, including via shocks (e.g., McNamara & Nulsen 2007; Somerville & Davé 2015; Naab & Ostriker 2017). The focus of this thesis is the exploration of these extended radio galaxies, through associating the radio sources with their optical hosts, and studying the dynamics and remnant population of a sample of low-luminosity sources.

This chapter is a review of the current position of research into radio galaxies and extragalactic radio surveys. To begin with, in Sections 1.1 to 1.6 radio galaxies are introduced, including a breakdown of the different features, morphologies, and classifications of radio galaxies. Their life cycles are also discussed, as the prevalence of restarting or remnant sources in the low-luminosity population is investigated in Chapter 5. Following this, Sections 1.7 to 1.11 cover an introduction to radio telescopes and surveys which provides context for the work in Chapters 3 and 4 that is focused on the use of radio survey images and catalogues. This introduction gives a brief history of instruments and surveys before discussing the most recent examples of both. The chapter ends by looking at the science aims and motivations of this thesis, and challenges faced by the new, large radio surveys.
1.1 Introduction to Radio Galaxies

There are two main galaxy populations that produce radio emission: those whose emission is dominated by star formation and those dominated by the active galactic nuclei (AGN). All active galaxies are fuelled by a central supermassive black hole (SMBH) which accretes matter from its surroundings, giving rise to an AGN. AGN are galaxies that emit more radiation (at a range of wavelengths) from accretion than from star formation. The radio emission produced by some galaxies has comparable contributions from both star formation and accretion. Distinguishing between the different origins of emission can be complicated (e.g., Padovani et al. 2017; Hardcastle et al. 2019).

Radio-loud AGN (RLAGN, radio-loud quasars and radio galaxies) are a subset of the active galaxy population in which the accretion of material on to the SMBH generates a relativistic jet of charged particles (consisting of electrons, positrons and/or protons) and magnetic fields (e.g., Begelman et al. 1984; Bridle & Perley 1984; Carilli et al. 1991; Laing & Bridle 2002a; Beall 2014; Croston et al. 2018). These jets can extend to mega-parsec (Mpc) in size and are extremely powerful, both in terms of kinetic luminosity and radiative signatures. The jets propagate into the surrounding medium of the host galaxy, where they create bubbles that expand through this medium, filled with the relativistic electrons that travelled up the jet. The observed radio emission is produced through synchrotron radiation, emitted by the electrons in radio jets being accelerated by multiple processes, including plasma processes, and internal and external shocks (see Section 1.3) (e.g., Gull & Northover 1973; Begelman et al. 1984; Bridle & Perley 1984; Laing & Bridle 2002a; Hardcastle & Croston 2020).

How a jet interacts with its environment can reveal a lot about a jet, such as its velocity, energy density and magnetic field content. Conversely, any known parameters about a jet can potentially be used to infer properties of the environment, where the environment cannot be observed directly. These characteristic and environment studies are important because jets impart large amounts of energy and momentum into their surroundings out to large scales (e.g., de Young 1991; Beall 2014; Kundt 2014). Because of this they play a crucial role in the evolution of their host galaxies and large-scale environments (e.g., Nesvadba & Lehnert 2008; Morganti et al. 2013; Kakkad et al. 2018; Mukherjee et al. 2018) through feedback processes (e.g., Fabian 1994, 2012;
McNamara & Nulsen 2007, 2012; Heckman & Best 2014; Somerville & Davé 2015; Naab & Ostriker 2017). Hot gas acts as a source of fuel for the AGN’s accretion processes, whilst also being a confining medium for the lobes to expand, work against, and deposit energy into (e.g., McNamara & Nulsen 2007, 2012; Heckman & Best 2014). This transference of energy is used to address the inconsistency between the observed and predicted star formation rates in galaxies and is applied in galaxy formation models to explain the suppression of star formation in massive galaxies at later times (e.g., Fabian 2012; McNamara & Nulsen 2007, 2012; Somerville & Davé 2015; Naab & Ostriker 2017).

1.2 FEATURES OF RADIO GALAXIES

RLAGN can be classified in different ways (see Section 1.4), however there are a couple of structural features that are common to most sources. Figure 1-1 shows two radio galaxies with differing morphologies and features. These features are introduced in this section, and the different morphologies are discussed in Section 1.4.

The **core** of a RLAGN refers to the central parsec-scale region. In most cases it is unresolved and generally it coincides with the host galaxy. At Gigahertz (GHz) radio frequencies, the integrated spectral index is flat (See Section 1.3), and thought to be dominated by synchrotron self-absorption at the base of the jets (e.g., O’Dea and Saikia 2021).

**Jets** are collimated, relativistic outflows produced near the SMBH. They can extend on scales ranging from kpc to Mpc (e.g., Pearson 1996).
Knots can be observed in the optical through to X-rays. They are localised regions of increased brightness. In FRIs they are possibly due to interactions between the jet plasma and slow or stationary objects whereas in FRIIs there are some knots that do not obviously disrupt the flow and may be due to magnetic field enhancements or internal shocks (e.g., Kraft et al. 2002; Hardcastle et al. 2003; Goodger et al. 2010; Mingo et al. 2017). In FRIs, inner jet knots are where the majority of the energy from the jet is dissipated. Throughout the jet they are where the jet is slowing down and becoming more turbulent.

A hotspot is a termination point of a jet. Here, the fast-moving jet interacts with a stationary object and causes shock acceleration. From the rest frame of the jet, it hits a wall of fast-moving material and stops suddenly. This wall of material is the outer edge of the expanding cocoon of accelerated plasma that forms the lobe (Myers & Spangler 1985; Meisenheimer et al. 1989; Carilli et al. 1991). They are at the working surface of the jet, compact in shape, and have a radio spectral index (see Section 1.7) of $\sim 0.5 < \alpha < 0.7$ (e.g., Blandford & Rees 1974). High resolution images of hotspots have shown some to have multiple components. It is thought that the jet terminates at the primary hotspot (Laing 1982; Hardcastle 2003) and that the secondary hotspots are either previous impacts from the movement of a precessing jet (e.g., Blundell & Rawlings 2001), or deflection of the primary impact off clouds or a previous cocoon wall (Williams & Gull 1985; Lonsdale & Barthel 1986). Hotspots can reveal the
nature of the physical processes occurring in the jet, for example termination shocks and reverse flows.

The variety of larger scale emission is described by the term lobe. For example, FRIs (see Section 1.4.1) often disperse into diffuse regions called plumes. However, in FRIIs the jets stay collimated for longer (See Section 1.4.2), see the top row of Figure 1-3 and Figure 1-4. Environmental interactions can affect the structure of the lobes. If a plume bends away from the axis of the jet, this is called a tail. Depending on the angle at which they turn away they can be wide-angle or narrow-angle tails (see the middle row of Figure 1-3 and Section 1.4.3). The gap between the bases of the lobes may fill with faint, diffuse emission. This is called a bridge. When the majority of the lobe is beyond the collimated jet then it is referred to a ‘plumed’, if the majority is between the start and end of the jet then it is referred to as ‘bridged’ (e.g., Heckman & Best 2014).

The emission mechanism that allows us to observe all these features is synchrotron radiation, which is introduced in the next section.

1.3 THE ORIGINS OF RADIO EMISSION

Baade (1956) and Burbidge (1956) confirmed that the emission from extragalactic jets was synchrotron radiation. A detailed description of the theory of synchrotron radiation can be found in Longair (2010) and Condon & Ransom (2016).

It is known that an accelerated charged particle emits electromagnetic radiation. When a relativistic charged particle interacts with a magnetic field it emits synchrotron radiation (if it is not relativistic, it emits cyclotron radiation). As the lightest particles are accelerated more easily in comparison to the heavier ones, it is the electrons and positrons that account for most of the synchrotron radiation observed. This radiation accounts for nearly all of the radio emission from AGN and dominates the continuum emission in star-forming galaxies (Longair 2010; Condon & Ransom 2016).
A single electron of mass $m_e$ and charge $e$, with a Lorentz factor of $\gamma$, in a uniform magnetic field $B$, will emit synchrotron radiation over a broad range of frequencies, which narrowly peak at a critical frequency $v_c$, given by:

$$v_c = \gamma^2 \frac{eB}{2\pi m_e}, \quad \text{Eq. 1-1}$$

In radio observations a power-law is often observed; for this to be the case the electrons’ energy must also have a power-law distribution. With the assumption of a power law extending from a minimum to a maximum energy, the energy spectrum of the electron can be given by $N(E) = N_0 E^{-p}$, then the total emissivity for a population emitting synchrotron radiation is given by:

$$J(v) = \int_{E_{\text{min}}}^{E_{\text{max}}} j(v)N(E) \, d(E) = \int_{E_{\text{min}}}^{E_{\text{max}}} j(v)N_0 E^{-p} \, d(E), \quad \text{Eq. 1-2}$$

where $j(v)$ is the emissivity of a single electron, which is a function of the critical frequency. From Eq. 1-1 and by assuming that the synchrotron spectrum is narrowly peaked, a full derivation can be found in Longair (2010):

$$J_{\text{syn}}(v) \propto N_0 v^{-\frac{p+1}{2}} B^{\frac{p+1}{2}}. \quad \text{Eq. 1-3}$$

The total emissivity is dependent on the magnetic field and the electron energy distribution. Therefore, in order to determine the effects of either on the emission from features of radio galaxies additional information is required as they cannot be separated through the synchrotron radiation alone.

The shape of the synchrotron emission spectrum is described as a function of the radio spectral index, $\alpha$, which is defined in terms of the flux density (Longair 2010; Condon & Ransom 2016):

$$S_p \propto v^{-\alpha}. \quad \text{Eq. 1-4}$$

Once there is no acceleration acting on the charged particle the energy will dissipate at a rate $\propto E^2$ (Komissarov & Gubanov 1994; Harwood et al. 2013; Condon & Ransom, 2016). This means the higher energy electrons will deplete their energy more rapidly. In areas like the lobes of a jet, where there is little acceleration occurring, the preferential cooling of the higher energy electrons leads to a steeper spectrum (one with an increased curvature) in regions containing older plasma (Harwood et al. 2013; Condon & Ransom 2016).
The emission from extragalactic radio sources is often dominated by the steep-spectrum emission from the lobes, and $\alpha$ ranges from 0.5 to 1.2 (e.g., Komissarov & Gubanov 1994). Active radio galaxies typically have integrated spectral indices of $\sim$0.7 (Laing et al. 1983; Sabater et al. 2019).

When a photon collides with a particle it can impart some of its energy to the particle; this is Compton scattering. Inverse Compton scattering occurs if a particle has sufficient energy that the photon will gain energy from the collision. With synchrotron radiation, the relativistic particles have enough energy to up-scatter photons to X-ray energies.

Figure 1-2 is a modified image from Harwood et al. (2013) showing an example model of spectral ageing and demonstrating the steeper curvature in older radio sources caused by synchrotron cooling and inverse-Compton scattering. Overlaid on to this image I have labelled some of the frequency bands used in radio observations, with the low frequency LOFAR Two-metre Sky Survey bands marked.

![Figure 1-2: Synchrotron spectra for a plasma with ages ranging from 0 Myr (red) to 10 Myr (purple). Overlaid are the observing frequency bands. Image adapted from Harwood et al. (2013).](image)
This graphical representation demonstrates the usefulness of low-frequency surveys with low flux limits in detecting the older emission in extended sources. Because of the faster energy loss at higher energies, the low frequencies are sensitive across a wide range of ages, while the higher frequencies miss older sources. As the bands increase in frequency the steepening and hence separation between the ages increase (see Section 1.6 for how this information is used). This creates a demand for higher sensitivity and deeper surveys at higher frequencies to detect the same emission as the low-frequency surveys.

Spectral ageing maps of radio galaxies demonstrate the changing in age across the source. In FRIs the flattest spectral indices occur at the core and inner jets, and in traditional FRIIs they occur in the hotspots. Moving away from these locations the index increases in steepness (Myers & Spangler 1985; Alexander & Leahy 1987; Harwood et al. 2013).

The dynamic age is an alternative way of calculating the age of a radio galaxy. Here the age of the radio source can be estimated by dividing the size of the source by its expansion speed (Alexander & Leahy 1987). The expansion speed is calculated using lobe length asymmetries (Scheuer 1995), by assuming it expands at the local speed of sound (Bîrzan et al. 2004), or through including X-ray observation of shock fronts (Croston et al. 2007; Croston et al. 2011).

However, the dynamic ages are often different from the spectral ages and can be up to an order of magnitude larger. Spectral ages are \( \sim 10^7 \) years and dynamical ages are in the range of \( \sim 10^8 \) or \( 10^9 \) years (Harwood 2013, 2015; Hardcastle & Croston 2020; Mahatma et al. 2020).

As extended radio galaxies are a small percentage of the population, low frequency surveys are again well suited for detecting them. These wide-area surveys with large fields of view can easily observe many objects in the local Universe and increase the chance of detection (Best & Heckman 2012), as well as being better suited to observing the older, extended emission. Deep surveys probe the population to higher redshifts, also increasing the chance of further detections (Smolčić et al. 2017; Tasse et al. 2021). Sections 1.8 to 1.11 cover radio surveys and telescopes in more detail, whilst Chapter 2 looks specifically at the surveys and data sets used in this thesis and compares the low-frequency LOFAR Two-metre Sky Survey to other established and contemporary radio surveys.
1.4 MORPHOLOGICAL CLASSIFICATIONS

Figure 1-3 shows a collection of jets and their morphological features, which will be introduced in detail in the following sections. On the top left is 3C 31, a typical FRI (see Section 1.4.1), where the strongest emission is in the central region, and the initially relativistic jets are decelerated on kiloparsec (kpc) scales into the extended plumes. On the right is 3C 98, an edge brightened FRII (see Section 1.4.2), where the jet is highly collimated and relativistic throughout, before terminating at hotspots. The middle two sources are examples of wide- and narrow-angle tailed sources discussed in Section 1.4.3, and the bottom row contains two restarting radio galaxies. The one on the left has typical double-double morphology. These types of radio galaxies are discussed in Section 1.6.
Figure 1-3 – A selection of radio galaxies showing different morphologies and features. The top row shows the FRI 3C 31 on the left with plumes and the FRII 3C 98 on the right with jets and hotspots (see Section 1.4 and Figure 1-1). The middle sources have the tails of a wide- and narrow-angle tailed source (3C 465 on the left and NGC 6109 on the right, see Section 1.4.3). The bottom left image is a double-double radio galaxy 3C 219 and bottom right is a restarting radio galaxy (see Section 1.6). Image from Hardcastle & Croston (2020) reproduced under the Creative Commons BY-SA 3.0 licence (https://creativecommons.org/licenses/by-sa/3.0/deed.en).
Traditionally RLAGN are split into two Fanaroff and Riley (FR) classes (Fanaroff & Riley 1974). There is a morphological difference giving two types of structures they found to be associated with high and low radio luminosity. The cause of this divide is often thought to be the jet’s interactions with the environment, though there is debate on the links between accretion mode and jet morphology (e.g., Hardcastle et al. 2007, 2009; Best & Heckman 2012; Gendre et al. 2013; Mingo et al. 2014, 2022; Ineson et al. 2015; Hardcastle 2018a). The FR classification is given by the ratio of the distance between the regions of highest brightness on opposite sides of the host galaxy to the overall source size (see Figure 1-1, the top row of Figure 1-3 and Figure 1-4). If the ratio is < 0.5 it is an FRI, where the peak of the radio emission is near the core. For a ratio > 0.5 it is an FRII, where the surface brightness is greatest near the edges of the lobes (e.g., Fanaroff & Riley 1974; Banfield et al. 2015; Miraghaei & Best 2017; Padovani et al. 2017).

The morphological divide between the FR classes is mainly explained as a difference in jet dynamics. The FRI morphology is due to deceleration via entrainment near to the core region, whereas FRIIs are relativistic out to a much greater distance, creating their edge-brightened morphology. (e.g, Bicknell 1984; Laing & Bridle 2002b; Heckman & Best 2014). Relativistic jet motion is demonstrated through very long baseline interferometry (VLBI) observations of apparent superluminal motion and the sidedness distributions of FRII jets (e.g., Bridle & Perley 1984; Mullin & Hardcastle 2009). It is also thought that jet power and local environment will determine how quickly a jet becomes decollimated (Gopal-Krishna et al. 1996). If you have two jets of the same power, at the host galaxy scale, if they are in a rich environment they will decelerate, entrain interstellar medium gas, and form FRI plumes. In contrast, in a poor host environment the jets will remain relativistic and collimated, forming FRIIs. There could also be a fundamental difference between the central engine and/or the composition of the jets (e.g., electron-protons vs. electron-positions). There is evidence of differences in the jet structure, and particle content (e.g., Celotti et al. 1997; Laing & Bridle 2002a; Croston et al. 2018; Harwood et al. 2020).

The luminosity divide led Fanaroff and Riley to propose two morphologically distinct classes with their low-resolution data. Later studies with higher resolution maps have revealed the differences discussed in Sections 1.4.1 and 1.4.2. FRIs are typically below $L_{178 \, \text{MHz}} \sim 10^{26} \, \text{W Hz}^{-1}$, whilst FRIIs are typically higher (Fanaroff & Riley 1974). This luminosity break was found to increase
proportionally to the host galaxy luminosity (Ledlow & Owen 1996). The host galaxy luminosity relationship (Ledlow & Owen 1996) was based on high frequency, flux limited, samples taken over a range of redshifts and varying environments for the FRI/FRIIs. In Mingo et al. (2019) a large sample of FRI and FRIIs were studied using a sensitive low-frequency survey, covering $z < 0.8$. They showed that, whilst there have been sources which have been exceptions to the luminosity break in the FR classes, there is in fact a population of low-luminosity FRIIs. It is this population that is the focus of Chapter 5.

High-excitation radio galaxies (HERGs) produce broad and narrow optical emission lines. The broad line region (BLR) emits broad emission lines and is found light days to light years away from the SMBH, between the accretion disc and the obscuring structure. The velocity dispersion of the region is up to several thousands of kms$^{-1}$, leading to Doppler broadening of the emission lines. The narrow emission lines come from a region (NLR) a few thousand light years from the SMBH, and beyond the obscuring structure (Kolb 2010). This is far enough away to always be visible no matter the viewing orientation. Here the dispersion velocities are a few hundred kms$^{-1}$. AGN with emission lines that are typically weaker or absent are referred to as low-excitation radio galaxies (LERGs) (e.g., Heckman & Best 2014; Hardcastle & Croston 2020).

A strong overlap with HERG/LERG classification and FRI/FRII morphology exists. Most FRIs have no emission lines and are typically LERGs. In contrast, FRIIs were traditionally considered to be mostly HERGs with a subset of sources that had weak or no emission lines (Best et al. 2005). However, Mingo et al. (2022) have demonstrated with their expanded population of lower luminosity FRIIs that LERGs are more prominent in the FRII population than was previously understood.

1.4.1 FRI

FRIs are centrally bright (see Figure 1-4), where the inner jet is highly relativistic. An FRI structure can range from parsecs (pc) to megaparsecs (Mpc) (e.g., Andernach et al. 1992). For distances $\lesssim 1$ kpc they reach speeds of $0.7 - 0.9c$, however within tens of kpc the bulk flow decelerates to $\lesssim 0.2c$ (e.g., Laing et al. 1999; Giovannini et al. 2001; Laing & Bridle 2002b; Canvin & Laing 2004). This rapid deceleration occurs as the jets interact with the host’s halos, entrain
material, and end in either a lobe or plume (Heckman & Best 2014). The deceleration may also be due to the jet opening angle (Krause et al. 2012).

The jets are overpressured relative to the surrounding medium, which leads to a low-density cavity which is inflated by the gas and leads to the plumes of the FRIs (e.g., Gull & Northover 1973; Bicknell 1984; Laing & Bridle 2002a). FRI lobes which are young and recently restarted are thought to expand supersonically through their surrounding medium (Croston et al. 2007; Heesen et al. 2014). In the older ones, the lobes and plumes expand sub-sonically.

Figure 1-4 – Two morphologically different galaxies as described in the text. Left is 3C 31 a centre-bright FRI, and right is 3C 47, an edge-bright FRII. Images from J. P. Leahy, A. H. Bridle, R. G. Strom, reproduced under the Creative Commons BY-SA 3.0 licence (https://creativecommons.org/licenses/by-sa/3.0/deed.en).

1.4.2 FRII

FRII jets are relativistic for much longer distances than those of FRIs and extend from hundreds of kpc to Mpc (see Figure 1-4) (e.g., Alexander 1987; Mullin et al. 2006). The jets terminate in hotspots where they hit slow moving material causing shock acceleration (e.g., Myers & Spangler 1985; Meisenheimer et al. 1989; Carilli et al. 1991; Heckman & Best 2014). Hotspots do not just occur at the edges, they can also occur at the base of a plume in a wide-angle tail source (see Section 1.4.3) (e.g., Hardcastle & Sakelliou 2004). The lobes of an FRII are formed from material that has travelled up the jet, and which upon hitting the hotspot (and abruptly decelerating) flows backwards to fill the area behind it (e.g., Longair et al. 1973; Heckman & Best 2014). The location of the hotspot
compared to the lobe may also depend on projection effects (e.g., Harwood et al. 2020).

The jet speeds in FRIIs are hard to calculate and measurements give different results depending on the method used. Speeds between 0.55 – 0.7\(c\) can be inferred by considering jet sidedness (the apparent difference between the primary- and counter-jet) and jet prominence (the ratio of the brightness to the total source flux) (e.g., Hardcastle et al. 1999; Arshakian & Longair 2004; Mullin & Hardcastle 2009). In order for the jets to maintain such high speeds they must interact weakly with their environment. At the hotspots the bulk advance speeds are difficult to determine but are thought to be within the range of \(~0.02 – 0.2c\) (e.g., Myers & Spangler 1985; Alexander & Leahy 1987).

FRIIs can have varied morphologies within the class, including X shaped and double-double radio galaxies. These differing morphologies are thought to be the result of episodic activity, see Section 1.6 (e.g., Mahatma et al. 2019), or a shift in orientation of the central engine (e.g., Dennett-Thorpe et al. 2002).

FRIIs are expected to have a luminosity over \(L_{178\,\text{MHz}} \sim 10^{26}\) W Hz\(^{-1}\). When automatically classifying the LoTSS DR1 sources Mingo et al. (2019) found that \(~51\%\) of their FRIIs were up to 3 orders of magnitude below this value. They concluded that either they are a population of older, fading sources, or they are low-powered jets in low mass host galaxies. A sample of this population of low luminosity FRIIs (or FRII-lows) are the basis of the work in Chapter 5, including the exploration of whether they have the same source dynamics as their high luminosity counterparts, and if there is a high proportion of remnant/restarting sources (see Section 1.6).

As discussed in detail in Chapter 5, morphological classifications are not absolute and can depend on resolution and frequency (Rudnick 2021).

### 1.4.3 Other Morphological Classifications

There are other morphological classes which are used to describe radio sources including hybrids, and narrow-angle tailed (NAT) and wide-angle tailed (WAT) sources.

Hybrid radio galaxies have differing morphologies in each lobe (Gopal-Krishna & Wiita 2000; Harwood et al. 2020). As there are two different morphologies from
the same central engine these sources argue against a model in which the central engine controls morphology. Harwood et al. (2020) concluded that hybrids are intrinsically FRIIs, and they are most likely the result of orientation effects. In the vast majority of cases, it would appear that they are FRIIs containing bent jets and/or lobes lying at an angle to a straight jet.

Rudnick & Owen (1976) distinguish between three types of ‘relaxed’ radio sources. These sources are bent in shape and classed in to three groups: narrow- (NAT), intermediate- and wide-angle tail (WAT). A NAT has an angle < 20° and a WAT has an angle > 90°, defined as being the angle between the lines connecting the regions of highest surface brightness (Rudnick & Owen 1976). Head-tail, NATs and WATs are morphologies that are thought to be due to environmental effects. The jet opening angle may play a role in determining the large-scale morphology (Krause et al. 2012).

All types of tailed galaxies are located within clusters of galaxies and can be used as tracers for galaxy clusters. WATs are usually associated with the dominant cluster galaxies (Owen & Rudnick 1976; Mao et al. 2010) and it is thought that their bentness is due to ram pressure through cluster-cluster mergers (Sakelliou & Merrifield 2000; Mao et al. 2010; Missaglia et al. 2019). It is also thought that NATs can be curved through the ram pressure of higher velocity intracluster medium (ICM) possibly through cluster-subcluster mergers (Bliton et al. 1998). By placing a line which best bisects the tails, Rudnick & Owen (1976) were able to conclude that the tails point away from the cluster centre, possibly due to pressure gradient or buoyancy in the cluster field. A small group of NATs whose tails face towards the cluster centre was found by de Vos et al. (2021), possibly indicating those galaxies that have fallen past the pericentre of the cluster. Combined with the observations of NATs and WATs within clusters, and the circumstances under which they develop, studying bent jets can inform us about the environment surrounding radio sources.

It is believed that WATs remain relativistic and well collimated until they undergo a rapid deceleration which leads to shocks, that in turn lead to particle acceleration and then those particles (electrons) yield X-ray synchrotron emission (Mao et al. 2010; Missaglia et al. 2019). They are morphologically between FRI and FRIIs and this could be due to their environment. Two highly collimated jets travel out to tens of kpc but become disrupted causing FRI-like plumes to form (Hardcastle & Sakelliou 2004). Their multifrequency properties are similar to FRIs. They are typically LERGs, and in infrared their hosts appear
to be normal elliptical galaxies. They lack significant contribution from star formation, and they tend not to be extremely blue in colour. They are, however, more powerful at radio frequencies (Owen & Rudnick 1976; Rudnick & Owen 1976; Missaglia et al. 2019).

In comparison, NATs have lower radio luminosities and fainter optical magnitude (Rudnick & Owen 1976; Giacintucci & Venturi 2009). Within the NATs are head-tail sources which show sharp bends very close to the radio galaxy core, making it hard to distinguish both tails. These are not different from the classical NATs, just viewed edge-on (Terni De Gregory et al. 2017).

Though not a morphological classification, there is a further classification of FR0. The FR0 population contains low-powered sources whose core emission contributes to $\geq 10\%$ of their total emission, and yet there is no resolved (or only slightly resolved) extended emission out to no more than a few kpc (e.g., Sadler et al. 2014; Baldi et al. 2015, 2016). They are more numerous than the FRI/FRII populations, and have similar properties to the FRIs, only without the extended emission (Baldi et al. 2016, 2018). It can be argued that as FR0 are typically unresolved and the FR classification is morphological in nature, then when these sources are eventually resolved they can go on to be classified (Hardcastle & Croston 2020).

### 1.5 SMALL RADIO GALAXIES

Galaxy scale jets are resolved sources, so not FR0s, and typically low luminosity. Their sizes are such that they have escaped the environment at the core of their host but are still small enough to have a direct effect on the host’s evolution (Webster et al. 2021a, 2021b). Some of them are able to drive shocks into the interstellar medium of their hosts (e.g., Croston et al. 2007, 2009; Mingo et al. 2011, 2012; Hota et al. 2012; Webster et al. 2021). This is important, as evolution models include the effects of various shocks, such as those from supernovae, on star formation and galaxy evolution (e.g., Hopkins et al. 2014).

The smallest radio galaxies, physically, are the Compact Symmetric Objects (CSOs) at less than a few hundred parsecs. The Gigahertz Peaked Spectrum (GPS) sources are $\leq 1$ kpc and have a radio spectrum peak between $\sim 1$ and $\sim 5$ GHz. Finally, the Compact Steep Spectrum (CSS) sources lie between $\sim 1$ and $\sim 20$ kpc and have a radio spectrum peak below 500 MHz (O’Dea & Saikia 2021).
The relationship between the CSS/GPS and the larger radio galaxies is uncertain, however it is thought that CSS sources become GPS sources which in turn evolve into FRIs and FRIIs (e.g., O’Dea & Saikia 2021).

Figure 1-5 is a power versus linear size plot showing where all the different classifications of radio galaxies discussed in the previous sections lie in relation to each other. This shows that even though there is overlap between each of the classes there are still distinct regions for each, although it should be noted that sources lie between the classes and that the apparent lower densities of objects between the classes is partly caused by selection effects.

Figure 1-5 - A power vs linear size plot showing the different classifications of radio galaxies. Individual objects are represented with points and the coloured contours represent the source density. Image from Hardcastle & Croston (2020) reproduced under the Creative Commons BY-SA 3.0 licence (https://creativecommons.org/licenses/by-sa/3.0/deed.en).
1.6 **Life Cycle of Radio Galaxies**

As mentioned in Section 1.1, feedback from RLAGN plays an important role in the evolution of galaxies and the large-scale environment. RLAGN are known to go through recurrent phases of activity (Kapińska et al. 2015; Jurlin et al. 2021). The release of energy from SMBH occurs in cycles, with periods of activity and quiescence (Woltjer 1959; Marconi et al. 2004; Morganti et al. 2021). These differing phases are known as the AGN’s life cycle (e.g., Brienza et al. 2018, 2020; Jurlin et al. 2020, 2021; Shabala et al. 2020; Morganti et al. 2021).

An active SMBH is often indicated by radio emission and jets (see Section 1.1). The active phase typically lasts for a few tens of Myr (Wan et al. 2000; Turner & Shabala 2015). Shabala et al. (2020) suggest that the active radio galaxy population is well described by two different models. Although their fraction of remnants and restarters is lower than expected with their constant age model, it cannot be ruled out as a possibility. However, their second set of models based on a power-law age distribution, with a high number of short-lived sources can be in excellent agreement with the observed fraction of both active, and remnant and restarting sources, which is also in agreement with population studies demonstrating radio galaxies of varied and older sources up to ~1000 Myr (Hardcastle et al. 2019).

At the end of the active phase the signatures of activity such as cores, jets, and hotspots will disappear or become strongly diminished, and the lobes will become fainter and more diffuse due to the expansion of the plasma (Jurlin et al. 2021). The radio galaxy is entering its remnant phase when the jet activity stops or substantially decreases (Komissarov & Gubanov 1994; Brienza et al. 2017; Mahatma et al. 2018; Jurlin et al. 2021; Morganti et al. 2021). The models run by Brienza et al. (2017) suggest that for ~70% of the cases the duration of the remnant phase is < 50% of the active phase, and the total source ages are between $5 \times 10^7$ and $10^8$ years (see Fig. 6 in Brienza et al. 2017; Jurlin et al. 2021). It is also predicted that remnant structures will fade on a timescale of a few $10^8$ years due to dynamical expansion and radiative losses (Brienza et al. 2017; Godfrey et al. 2017; Hardcastle 2018a; English et al. 2019; Shabala et al. 2020; Morganti et al. 2021).
The remnant emission will have an ultra-steep spectrum because the electrons are not being replenished (e.g., Komissarov & Gubanov 1994; Jurlin et al. 2021; Morganti et al. 2021). These older lobes combined with an active central region can indicate a restarted radio AGN (e.g., Mahatma et al. 2019; Jurlin et al. 2020, 2021). Here the central engine has restarted its activity within the lifetime of the remnant lobes. Double-double radio galaxies (DDRGs) are consistent with the idea that multiple episodes of jet activity can be seen within the same radio galaxy. DDRGs have pairs of radio lobes along the same projected axis, where these inner lobes demonstrate recent activity and are within older, outer lobes. These are the result of interrupted and restarted activity (Schoenmakers et al. 2000; Mahatma et al. 2019; Shabala et al. 2020).

Shabala et al. (2020)’s active radio galaxy models predict a remnant and restarting population of \( \leq 5\% \) with the constant maximum age models. However, this value is strongly dependent on redshift, flux density, and angular size. If the fraction of genuine restarted sources is \( > 10\% \) then this would imply that there is a high fraction of short-lived and/or low-powered sources (Shabala et al. 2020). Mahatma et al. (2018) found \( \leq 9\% \) of their radio galaxy population to be remnants and in Mahatma et al. (2019) they found that 4\% of their population were DDRGs. Jurlin et al. (2020) found that 13-15\% of their population were restarters with new core activity co-existing with remnant lobes. This also includes anything classed as a DDRG. The different stages of the life cycle are summarised in Figure 1-6, with example images of radio galaxies in each of the different phases.

As discussed in Section 1.3, the lowest frequencies (<1 GHz) are the last part to be affected by radiative losses. The presence of a break in the power-law spectrum with a steepening of the spectral index at higher frequencies can be used to indicate the ageing of electrons (Jurlin et al. 2020, 2021; Morganti et al. 2021). If \( \alpha > 1.2 \) this implies that the plasma has no new particle injection, and this is an indicator of a remnant radio galaxy (see Section 1.3 and Figure 1-2) (e.g., Komissarov & Gubanov 1994; Jurlin et al. 2020, 2021; Morganti et al. 2021). The lower the frequency this occurs at the larger the time span since the central engine switched off. Therefore, if the steepening occurs at higher frequencies this indicates a younger remnant radio galaxy.
Large and deep surveys make it possible to see all phases of the life cycle as it is harder to detect radio galaxies in the remnant and restarting phase. For the work in this thesis, the LOFAR Two-metre Sky Survey (LoTSS) is well suited for studying the life cycle of radio galaxies because of its surface brightness sensitivity and high resolution of 6 arcsec at low frequencies (see Section 2.1.1) (Shimwell et al. 2017).
Figure 1-6 – The different phases of the life cycle of a radio galaxy with example images. The images in (a) and (b) are adult active galaxies (Images: (a) left - Volker Heesen, right - R. Timmerman; (b) Cyril Tasse; all – The LOFAR surveys team). Two example remnant radio galaxies are shown in (c) from Morganti et al. (2021). The left one has been selected for morphology and the right one for its ultra-steep spectrum, see Section 5.4.4. In (d) there are two DDRGs. The one on the right is a 13 cm wavelength image from ATCA by L. Saripalli, R. Subrahmanyan and Udaya Shankar. The lefthand one is from Mahatma et al. (2019) and shows the darker VLA contours overlaying the orange LOFAR contours. At the bottom (e) has Morganti et al. (2021)'s examples of restarting radio galaxies with the lighter FIRST contours demonstrating the restarting activity. In the bottom left corner (f) shows the radio contours of TXS 0128+554, a recently active jet. Its signature shows that it is a young jet with recurrent activity (Lister et al. 2020). Images reproduced under the Creative Commons BY-SA 3.0 licence (https://creativecommons.org/licenses/by-sa/3.0/deed.en).
Most of the data that I have used throughout this work has come from modern radio telescope arrays. This section briefly describes how these arrays work.

How much fine detail can be seen in an image is given by the angular resolution of the telescope. The resolution of a telescope is the minimum angular distance between two distinguishable objects and can be used sometimes to refer to the resolving power of a telescope. This is the ability to see two distinct objects far away as two separate images. The Rayleigh criterion defines the angular resolution as the angular separation where the maximum of each source lies in the first minimum of the diffraction pattern of the other. For a telescope it is given as $\theta \sim \lambda/D$ where $\theta$ is the angular resolution in radians, $\lambda$ is the wavelength observed, and $D$ is the diameter of the antenna/telescope. For an array, $D$ is the maximum physical separation of the telescopes (the baselines). For a given wavelength, angular resolution is improved by increasing the diameter of the telescope, or the baseline length. As radio waves have such long wavelengths, to achieve arcsecond or sub-arcsecond images would require telescopes with diameters kilometres across. Building a single telescope of this size is not feasible.

To observe with telescopes of this size, radio interferometry and arrays are employed. This is the use of aperture synthesis, where a group of telescopes combine their signals to produce images that have an angular resolution of a single telescope with a diameter of the size of the largest separation in the collection.
As described by Jackson (2008) and Thompson (2017), the basic principle of interferometry relies on Young’s slits fringe pattern. Here a single point source emitting coherent radiation that passes through two slits demonstrates interference fringes with constructive and destructive interference. The separation in the fringes is $\frac{\lambda}{d}$: the wavelength divided by the slit separation.

An extended source can be considered a sequence of point sources each one emitting radiation that is uncorrelated with each other. The sum of the individual angular displacements in the source creates an equal but oppositely directly displacement in the fringe pattern. This will be the total interference of the extended source. If the source size is $\sim \frac{\lambda}{d}$ then the interference has created constant illumination.

If $d$ is decreased, then larger source sizes can be viewed. Small sources have a high visibility out to large slit separations, whereas the visibility of large sources falls off rapidly as slit separation increases. Interferometers use dishes/antennas/stations to interfere signals in a way analogous to slits and generate an interference pattern as a function of delay.

Figure 1-8 shows a simple example of two antennas set a distance, $B$, apart. The separation, $B$, of these antennas is the baseline. Because of this separation, the radio waves from the source will be received by them at two different times. Focusing now becomes the act of combining the individually received images into each antenna together. However, because of this delay they will all have different phase offsets, so timing is crucial (Jackson 2008; Thompson et al. 2017). Atomic clocks at the telescope can time stamp the observations to an accuracy of a few billionths of a second\(^1\).

\(^1\)https://public.nrao.edu/telescopes/radio-telescopes/
The phase delay is $kB \cdot s$ where $k = \frac{2\pi}{\lambda}$. Therefore, if the signal received by one antenna is $E$ then the signal received by the other is $E e^{i kB \cdot s}$. As an extended source is the sum of infinitesimally small point sources the response is given by summing the interference pattern generated by each point source:

$$R = \int I(\sigma) e^{i kB \cdot (s+\sigma)} d\sigma,$$

Eq. 1-5

where $I(\sigma)$ is the intensity distribution of the sky, and $s + \sigma$ is the vector in the direction of a small part of the source. As $\sigma$ is parallel to $b$ then $B \cdot \sigma = b \cdot \sigma$ and:

$$R = e^{i kB \cdot s} \int I(\sigma) e^{i k b \cdot \sigma} d\sigma.$$

Eq. 1-6

As the first term contains only known constants and is based on the array geometry it is ignored in the integral. Using Cartesian coordinates with the unit vectors $i$, $j$, and $k$ to define $\sigma = xi + yj + zk$ and $b = ui + vj + wk$ then $b \cdot \sigma = ux + vy + zw$ and:

$$R(u,v,w) = \iiint I(x,y,z) e^{2\pi i (ux+vy+wz)} dx \, dy \, dz.$$

Eq. 1-7
This is the Van Cittert-Zernicke theorem and clearly demonstrates that the response is a Fourier transform of the source intensity distribution. The $wz$ term is ignored for simplicity, and is usually taken into consideration when the observations are performed in the low frequency bands and the field of view is large (see Section 2.3.4).

To obtain a sky intensity map from the measured response, an inverse Fourier transform is performed. Therefore, to improve the overall quality of the images an increased $uv$-coverage is needed.

If many baselines are present, then many simultaneous measurements can be taken in the $uv$-plane. The more of the $uv$-plane that is filled the more accurate a map of the sky intensity distribution can be generated. The image is improved as the Earth rotates. The rotation changes the angle between the antennas and the source, and the size of the baselines between the two antennas. This in turn further changes the phase delays between the two antennas (Jackson 2008; Thompson et al. 2017).

Another option is that more antennas could be built. This will certainly fill gaps in the $uv$-coverage; however, the number of antennas is usually set during the construction phase. It does mean though that part of the array can be built and used whilst the rest remains under construction. This is the principle behind the Square Kilometre Array precursors\(^2\) (see Section 1.9). The $uv$-coverage can be increased through the location design of the antennas and taking advantage of the Earth’s rotation through observation time. For example, placing the antennas in a logarithmic spiral such as the remote stations placement for LOFAR\(^3\) (See Section 2.1). The other option is to allow the antennas to move like the VLA (e.g., Kellermann et al. 2020) (see Section 2.2).

The combination of the Earth rotation and antenna placement increases the number and varies the size of the projected baselines within the array. Longer baselines record small-scale structures in sources well but are insensitive to larger scale structures. As the source becomes larger than $\frac{\lambda}{D}$ the fringes wash out. The various sized baselines allow for different spatial scales leading to the imaging of both compact features (longest baselines) and extended emission

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2 https://www.skao.int/en/explore/telescopes/357/interferometry  
3 https://science.astron.nl/telescopes/lofar/lofar-system-overview/technical-specification/lofar-array-configuration/
(shortest baselines) (Jackson 2008; Thompson et al. 2017; Kellermann et al. 2020).

It is not possible to sample the whole $uv$-plane, therefore the inverse Fourier transform gives a ‘dirty’ image:

$$I_D(x, y) = \iiint I(u, v)S(u, v)e^{2\pi i(ux+vy)} \, du \, dv,$$

Eq. 1-8

where $S(u, v)$ is a sampling function that equals one where the regions have been sampled and zero otherwise. As $I_D(x, y)$ is defined as a Fourier transform of a product of two functions $I(u, v)$ and $S(u, v)$, then the convolution theorem states that the dirty image is a convolution of the true sky image with a Fourier transform of the sampling function:

$$I_D(x, y) = I(x, y) * B(x, y),$$

Eq. 1-9

where:

$$B(x, y) = \iiint S(u, v)e^{2\pi i(ux+vy)} \, du \, dv,$$

Eq. 1-10

is called the dirty beam. Therefore, in order to obtain a ‘clean’ image of the sky unwanted interference is removed, the dataset is calibrated for effects such as those from the telescope and atmosphere, and the effects of the dirty beam are cleaned. This process is described in detail in Chapter 2. Additional effects on the quality of an image are bandwidth and integration time smearing. These occur at large distances from the centre of the pointing, and limit the effective field of view in wide field images.

Interferometers have a lower sensitivity to interference, as interference does not correlate, and interferometry is about correlating two signals. The type of interference which causes problems is that which saturates or disables the receiver. This is dealt with by dividing the observing band into spectral channels/windows and removing them (see Section 2.3.2).

A full array will have each antenna working in conjunction with each other antenna creating multiple, ever-changing baselines and phase delays. All of these datasets are then transported to facilities for processing and calibrating.
1.8 Far and Wide – The Radio Surveys

A major element of this thesis work is the development of a complex image analysis software program, which relies on the results of new, innovative radio surveys and is improving them. This section briefly introduces the history of radio instruments and surveys and looks at some of the modern examples. Following this in later sections is a brief discussion of the goals of radio surveys, and the challenges faced by these new, large telescope arrays.

As technology has improved, this has allowed radio continuum surveys to develop in parallel. In the 1950s there were many surveys between 100 – 400 MHz which typically had low resolution and low sensitivity. Added to this, the lack of advances in data handling and storage became a major problem. However, by the 1970s computer techniques had improved enough to deal with handling large data sets and displaying images (Wielebinski 2003).

The first large radio survey was the 2C catalogue in Cambridge, in 1955, which had 1936 discrete radio sources (Shakeshaft et al. 1955; Hazard & Walsh 1959). Unfortunately, due to poor sensitivity and angular resolution there were significant errors due to noise, and confusion between nearby unresolved sources (Hazard & Walsh 1959; Kellerman & Wall 1987). Between 1957 and 1958 the Mills Cross interferometer, in Sydney, published a survey which did not contain the same magnitude of errors as 2C (Mills & Slee, 1957; Hazard & Walsh 1959). Cambridge then carried out further surveys during the period of 1959 to 1962, the most notable of these are the 3C, 3CR, 3CRR and 4C surveys (Edge et al. 1959; Bennett 1962a, 1962b; Gower 1966; Laing et al. 1983). The results of these produced source counts in agreement with the Sydney survey (Hazard & Walsh 1959). These surveys started the development of radio astronomy with new telescopes, research groups and surveys.

Between the 22-year period of 1969 and 1991, an understanding of the properties of AGN and the physical processes driving them was built (e.g., Bolton et al. 1979; Otrupcek & Wright 1991; Norris 2017). The Parkes telescope was built with a large frequency range, between 80 MHz – 22 GHz, and improved positions and optical identifications, and redshifts obtained for many sources (Otrupcek & Wright 1991). The VLA was also operating during this period, as it was completed in 1980, see Section 2.2 for details. The VLA is a
ground-breaking telescope designed with the expectations of studying a variety of areas such as Doppler-shifted hydrogen emission from nearby galaxies and resolving the fine-scale structure of powerful radio galaxies, quasars, and supernovae remnants (Thompson et al. 1980, Perley et al. 2011, Kellermann et al. 2020). It was able to observe radio sources classed as extended galaxies or probable galaxies, and quasars in the 3CRR catalogue (the follow-up to the 3CR catalogue) and determined that 65 – 80% of weak radio galaxies and 40 – 70% of quasars have jets. It also had the capacity to observe the fine-scale structure of radio galaxies (Bridle & Perley 1984).

This saw the start of a transitional period between 1990 and 2011. Here new technology led to more sensitive telescopes and over a hundred times more known radio sources. This era was dominated by four major surveys. The Westerbork Northern Sky Survey (WENSS) ran between 1991 and 1996 and was the product of the collaboration between the Netherlands Foundation for Research in Astronomy (NFRA/ASTRON) and Leiden Observatory. It is a low-frequency survey centred at 327 MHz, covering everything north of $\delta = +30^\circ$, creating a catalogue of $\sim$230,000 sources at a resolution of 54 arcseconds (Rengelink et al. 1997; Kimball & Ivezić 2008). During this period, between 1993 and 1996, the National Radio Astronomy Observatory (NRAO) VLA Sky Survey (NVSS) covered the whole of the northern sky for $\delta > -40^\circ$. This 1.4 GHz survey produced images at a resolution of 45 arcseconds and is still one of the largest published radio surveys at $\sim$1.8 million sources (Condon et al. 1998; Best et al. 2003; Kimball & Ivezić 2008). At the same time using the VLA the Faint Images of the Radio Sky at Twenty-centimeters (FIRST) survey was started in 1993. It was completed in 2011, after being extended to cover the Sloan Digital Sky Survey 3 area. Although it covers a smaller area to NVSS, this 1.4 GHz survey is complementary to the other. It has a higher resolution, of 5 arcseconds, and a greater sensitivity, allowing the detection of some sources not found in NVSS, but it is not as sensitive to the extended emission as NVSS (Becker et al. 1995; Kimball & Ivezić 2008; Helfand et al. 2015). In contrast, between 1997 and 2007 the Sydney University Molonglo Sky Survey (SUMSS) covered the whole of the southern sky for $\delta < -30^\circ$ with a resolution and sensitivity similar to that of NVSS. The Molonglo Cross telescope catalogued $\sim$210,000 sources at 43 arcsecond images (Bock et al. 1998; Mauch et al. 2003).
There were many surveys during this period, however these had the greatest impact by increasing the number of known radio sources from tens of thousands to ~2.5 million (Norris 2017). In the case of NVSS and FIRST, for example, they are still widely used today. These surveys are included in Table 2-1 comparing surveys in Section 2.1.2. As with all continuum surveys their science aims were varied. These included star formation and galaxy evolution, cluster identification and evolution, cosmology, and cross-matching with other surveys for optical identifications to obtain redshifts (Becker et al. 1995; Rengelink et al. 1997; Bock 1998; Condon et al. 1998). These science aims are discussed in greater detail in Section 1.10.

1.9 CURRENT AND UPCOMING SURVEY FACILITIES

Taking a more recent perspective of radio astronomy, we can see that advances in technology have allowed for new designs of telescope to be built, for existing ones to be improved, and, with the surveys which are now being carried out, a new transitional era is beginning. Recently technology has moved away from building large dish telescopes and into building aperture arrays. Here, instead of focusing, like a large dish, via reflection, the aperture arrays focus by electronically varying the phase, or delay, across the aperture. The weighted sum of all the receiving antenna creates a larger field of view, see Section 1.7 (Garrett 2012). Those telescopes like ASKAP with phased array feeds, not only offer large and multiple fields of view, and rapid electronic steering, but they also improve performance, reliability, and cost. These technological improvements are allowing astronomers to go back and look again at lower frequencies, allowing observations to be made up to higher redshifts (van Haarlem et al. 2013; Shimwell et al. 2017; de Gasperin et al. 2021).

Over the next couple of paragraphs, I will introduce a few telescopes with their recent or current surveys, starting with the two in Western Australia. The Murchison Widefield Array (MWA) spans over 3 km and is made up of 4,096 antennas in 256 tiles. It observes over a frequency range of 70 – 300 MHz and has a variety of scientific aims as it scans the Southern hemisphere (Tingay et
This includes the GaLactic and Extragalactic All-sky MWA (GLEAM) and GLEAM-X surveys. GLEAM surveyed everything south of $\delta = +30^\circ$ from 2013 to 2017 at a frequency of 200 MHz. After the 2017 upgrade to the MWA GLEAM was extended to the GLEAM-X survey, between 2018 and 2020, with higher resolution and greater sensitivity. GLEAM detected $\sim$300,000 sources and in its first data release GLEAM-X has catalogued $\sim$80,000 sources (Wayth et al. 2015; Hurley-Walker et al. 2017; 2022).

The second in Western Australia is the Australian SKA Pathfinder (ASKAP). ASKAP uses a novel technological approach to achieve a high survey speed. Here, thirty-six 12 m dish antennas are arranged over 6 km baselines. Each antenna is equipped with a phased array feed (PAF) of 36 separated beams mosaicked into one wide field of 30 deg$^2$. These allow for the wide field of view and rapid survey capability when combined with the high performance computing facilities in Perth. Each PAF has the capacity to observe over a frequency range of 700 – 1800 MHz (Johnston et al. 2007). For ASKAP the continuum survey is the Evolutionary Map of the Universe (EMU). It will cover everything south of $\delta = +30^\circ$, and it will be 45 times more sensitive than NVSS. The pilot survey has released a catalogue of $\sim$220,000 sources for the same sky area as the Dark Energy Survey (Norris 2011, 2017; Norris et al. 2021). More recently the Rapid ASKAP Continuum Survey (RACS) was started in 2020 to test the capacity of the PAFs. It took just 300 hours to map $\sim$3 million galaxies in the southern sky, $\delta < +41^\circ$. The first data release was performed at 887.5 MHz, but future iterations will cover the 1295.5 and 1655.5 MHz frequency abilities of the receivers. This rapid survey technique allows the sky to be observed at different frequencies quickly, it allows for repetitions of the survey to be made and differences to be logged, and it also allows for easier follow ups to transient sources (McConnell et al. 2020).

Located in India, the Giant Metrewave Radio Telescope (GMRT) covers a frequency range of 50 to 1500 MHz. It consists of 30 antennas covering 25 km (Swarup 1991). Its low-frequency all-sky survey is the TIFR GMRT Sky Survey (TGSS) at 150 MHz. This was carried out between 2010 and 2012, and there has since been improvements made to the data processing. The Alternative Data Release 1 forming a catalogue of 0.62 million sources is now available, covering the area between $\delta = -53^\circ$ to $\delta = +90^\circ$ (Intema et al. 2017).

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4 https://www.mwatelescope.org/
6 https://research.csiro.au/racs/
The Westerbork Synthesis Radio Telescope (WSRT) has been operational since 1970. Since then, the APERTure Tile In Focus (APERTIF) upgrades were finished in 2018. This installed PAFs on the 14 antennas, similar to ASKAP. This array covers 2.7 km and can observe across frequencies from 1 GHz to 1.7 GHz. Large scale surveys on APERTIF started in 2019, but it is clear that the pandemic has affected observing plans. This however has not prevented first images from being produced, only large survey catalogues. It is hoped that these surveys will cover areas such as nearby sources for spectral indices and spectral curvature maps, diffuse emission from clusters and very distant radio sources, and areas of cosmology including the Sachs Wolfe effect, and autocorrelation function and cosmic magnification (Röttgering et al. 2011; Apertif Science Team 2016; Kutkin et al. 2022).

Throughout my thesis I make extensive use of data from the LOw Frequency ARray (LOFAR) and the Karl G. Jansky Very Large Array (VLA), complemented with images from MeerKAT and data from large public catalogues. Therefore, each of these telescopes and datasets, and how they relate to my work, are discussed in detail in the next Chapter.

Section 2.1 discusses LOFAR in detail. This is a pan-European low-frequency array with a variety of surveys spanning its 10 – 240 MHz range. Many of the surveys involve only the central core and remote stations in the Netherlands, however more recent work has improved the calibration and data processing for the international baselines. The Multifrequency Snapshot Sky Survey (MSSS) was a shallow continuum survey that made a first pass of the northern sky (Heald et al. 2015). More recently is the LOFAR LBA Sky Survey (LoLSS) aiming to observe the entire northern sky between 42 – 66 MHz, providing ultra-low-frequency information for hundreds of thousands of radio sources (de Gasperin et al. 2021). The LOFAR Two-metre Sky Survey (LoTSS) is the main continuum sky survey, see Section 2.1.1. As LOFAR is focused on low frequencies it is able to detect older emission allowing observations of sources at higher redshifts. With higher sensitivities and longer baselines, fainter structures can also be seen (e.g., Shimwell et al. 2019; Morabito et al. 2022).

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7 https://www.astron.nl/telescopes/wsrt-apertif/
8 https://www.astron.nl/announcement-wsrt-apertif-surveys-to-continue-throughout-2021/
In 2011 the Very Large Array finished upgrading to the Karl G. Jansky Very Large Array (referred to indistinctly as VLA/JVLA). This upgrade greatly improved its sensitivity and bandwidth and is discussed in detail in Section 2.2 (Perley et al. 2011; Kellermann et al. 2020). The low frequency survey on the VLA has recently been re-reduced to produce the VLA low-frequency Sky Survey Redux (VLSSr) at 73.8 MHz. Despite having a lower resolution and sensitivity the VLSS (and VLSSr) acts as a low-frequency anchor point to many multiwavelength studies, it also provides a model that can be used for simulations and preliminary calibration for other low-frequency arrays (Lane et al. 2014). The currently-ongoing continuum survey, started in 2017, is the VLA Sky Survey (VLASS). It will be carried out in 3 epochs and the data is being released as a set of quick-look images followed up with improved self-calibrated single-epoch images (Lacy et al. 2020).

Another recently completed facility is the South African MeerKAT array. As I have made use of data from the MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE) survey I discuss MeerKAT in more detail in Chapter 2.

One of the most ambitious radio telescope projects yet to be completed is the Square Kilometre Array (SKA). The SKA Observatory (SKAO) is a collaboration of 16 countries (with eight more petitioning to join), as well as eight African partner countries involved with future expansion projects. Across 20 countries, ~100 organisations have been participating in development, design, and construction of the SKA telescope⁹. The SKAO will comprise of two separate arrays, one in Western Australia and one in South Africa, as well as the headquarters at Jodrell Bank Observatory in the United Kingdom (García-Miró et al. 2019; Paragi et al. 2019).

The array in Western Australia is the SKA-Low. When complete it will contain 131,072 log-periodic, Christmas tree like, antennas in 512 stations, spread over a collecting region of 400,000 m² giving a maximum baseline of 65 km, and a maximum resolution of 4 arcsec. As the name implies this will be the low frequency array, observing in a range of 50 – 350 MHz (Braun et al. 2019; García-Miró et al. 2019; Paragi et al. 2019)¹⁰. In comparison, the South African component will be made up of the 13.5 m dishes that already comprise the MeerKAT telescope (see Section 2.4 for details) and the 15 m dishes to complete the SKA-Mid telescope. The total 197 dishes will form a central 1 km core and

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⁹ https://www.skao.int/en/partners

¹⁰ https://www.skao.int/en/explore/telescopes/ska-low
three logarithmic spiral arms (the same as the SKA-Low) with a maximum
distance between two dishes being 150 km, generating an overall collecting area
of 33,000 m$^2$ and obtaining resolutions up to 0.7 arcsec. The SKA-Mid will
observe at mid-range frequencies, covering 250 MHz – 15.4 GHz with the
possibility of achieving 24 GHz (Braun et al. 2019; García-Miró et al. 2019;
Paragi et al. 2019)$^{11}$.

The SKA is a multi-purpose radio telescope, and as such will be able to carry out
both HI and continuum surveys. This means that its science goals are extensive
and varied, covering many areas such as dark energy and dark matter,
gravitational waves, evolution of stars, galaxies and black holes, cosmic
magnetism, radio transits, planetary evolution, studies of the Milky Way, and
our sun (Johnston et al. 2007; Paragi et al. 2019)$^{12}$.

Due to the size and scope of the SKA many of the current telescopes and
surveys are either SKAO precursors or pathfinders. A precursor telescope is
based at an SKAO site carrying out work related to future activities and is part of
the development and testing of SKA technology. These precursors include the
Murchison Widefield Array (MWA) and the Australian SKA Pathfinder (ASKAP) in
Australia, and MeerKAT in South Africa, which will ultimately become part of the
SKA-Mid telescope. Pathfinders are all around the world and are involved in the
science and technological studies for the SKAO. These include APERTIF, the
Giant Metrewave Radio Telescope (GMRT) and the LOw Frequency ARray
(LOFAR) (Norris 2011)$^{13}$.

$^{11}$ https://www.skao.int/en/explore/telescopes/ska-mid
$^{12}$ https://www.skao.int/en/explore/science-goals
$^{13}$ https://www.skao.int/en/explore/precursors-pathfinders
1.10 **Survey Science Goals**

**Overview**

Most radio surveys are divided into those which focus on the detection of the HI emission line and continuum surveys which observe over a range of frequencies. The main focus of my thesis work is with continuum surveys, so this section discusses their science goals, in particular those which relate to the telescopes and surveys discussed in Sections 1.9, 2.1.1 and 2.4. As different continuum surveys observe over different frequency ranges and different sky areas, they allow vast samples of galaxies to be studied. The varying resolution and sensitivity of these surveys provides the opportunity to study galaxies at different stages of evolution, as well as aspects of cosmology. All these telescopes and surveys cover a vast range of science goals. Given the broad range of science topics covered, an exhaustive description is beyond the scope of this thesis. Therefore, the following is a brief description of a few of these science goals. This is in no way meant to be complete, and the best way to explore what each survey team or telescope are hoping to achieve is through their publications and science working groups. For many of those discussed in Section 1.9 these can be accessed through the following:

- [http://emu-survey.org/publications.html](http://emu-survey.org/publications.html) (EMU)
- [http://www.ncra.tifr.res.in/ncra/RecentResults](http://www.ncra.tifr.res.in/ncra/RecentResults) (GMRT)
- [https://lofar-surveys.org/publications.html](https://lofar-surveys.org/publications.html) (LOFAR)
- [https://www.mighteesurvey.org/publications](https://www.mighteesurvey.org/publications) (MIGHTEE)
- [https://science.nrao.edu/vlass/community/science-working-groups](https://science.nrao.edu/vlass/community/science-working-groups) (VLASS)

Radio surveys are carried out to explore many of the unanswered questions, including those surrounding extragalactic jets. For example, how are jets triggered? What can the classification or morphology of jets tell us about their evolution? What extent is the role of jets in the feedback processes? These all link to our understanding of star-formation (SF), active galactic nuclei (AGN) evolution, galaxy clusters, large-scale structure of the universe and cosmology.
As always, it is hoped that with more extensive surveys over a greater variety of frequencies we will be able to study all of these and more (Tadhunter 2016; Simpson 2017, Hardcastle et al. 2019, Paragi et al. 2019).

Next generation radio surveys will be able to accurately measure the evolution of the cosmic star-formation rate (SFR) to high redshifts. Synchrotron emission generated by cosmic-ray electrons accelerated by supernovae shocks is proportional in strength to the far-infrared (FIR) emission, which in turn is proportional to SFR. As radio is unaffected by dust extinction it can be used to measure SFR, allowing radio continuum surveys to be an excellent tool for studying cosmic SFR (Beswick et al. 2015; Norris 2017; Shimwell et al. 2017; Paragi et al. 2019).

There are many surveys looking at the evolution of AGN and the feedback mechanisms associated with them. These feedback mechanisms are important as without them simulations predict the formation of too few large galaxies and too many smaller galaxies (e.g., Silk 2011). The evolution of AGN is also linked to restarting and remnant radio galaxies (see Section 1.6), and radio loudness (e.g., the review by Hardcastle & Croston 2020; Jurlin et al. 2021; Mingo et al. 2022 and the references within these), and these radio surveys are researching the links between AGN evolution, SF evolution, properties of different classes of AGN and how they are related to accretion mode (Wayth et al. 2015; Apertif Science Team 2016; Smolčić 2016; Norris 2017; Paragi et al. 2019; Norris et al. 2021).

Many radio surveys are looking at aspects of the large-scale structure of the universe, for example, galaxy clusters and cosmic magnetism (e.g., Wayth et al. 2015; Paragi et al. 2019). A galaxy cluster is located at intersections in the cosmic web. They consist of galaxies within intergalactic gas. The radio emission from a cluster can come from the radio galaxies in the cluster itself, such as the wide-angle and narrow-angle tailed sources which will be interacting with their environment (Terni De Gregory et al. 2017). The emission can also be associated with radio relics. These are elongated, diffuse objects in the outskirts of the cluster with no obvious galaxy counterpart. They are thought to be the result of shock structures formed in galaxy mergers (Komissarov & Gubanov 1994; Brüggen et al. 2012). It is thought some radio jets also lift gas from their host galaxies (Morganti et al. 2021). Similar in structure to these, radio halos are diffuse emission spanning a large part of a galaxy cluster. Surveys are using
these sources of radio emission to study the galaxy clusters individually, and to aid research into large-scale structure and cosmology.

With the improvements in technology many of the upcoming surveys and instruments are looking at using radio to explore many areas of cosmology. This includes using weak gravitational lensing to look for dark matter, looking at the cosmic history and seeing how gravity, dark energy, and dark matter shape the large-scale structure of the intergalactic medium during the first billion years (Wayth et al. 2018; Paragi et al. 2019). There are plans for the SKA to work in conjunction with gravitational wave interferometers.

1.11 Challenges Faced by Radio Surveys

The upcoming and current instruments and surveys face many challenges as they grow in size and complexity, not least of which are those technical challenges arising from the large volumes of data produced. This ‘big data’ will require advanced storage facilities and new strategies for handling the distribution of the data. Along with this comes the immense processing power required for both the observations and the computational work of data intensive research. This will also require high power consumption, new and consistent methods of accessibility, and curation, as well as high bandwidth for data transfer, and data storage solutions (Norris 2011; Jones et al. 2012). To give an example of the expected data requirements of the SKA, the transfer rates of data from the SKA-Mid to the local processing facility in Cape Town is anticipated to be ~100,000 times faster than the projected global average home broadband speed for 2021. The data will be transferred to supercomputers that have the processing speed of ~135 PFlops, and the SKA is expected to archive 300 petabytes of data a year, which is the same storage as about half a million laptops.

Another of the biggest challenges for the latest surveys is radio frequency interference (RFI) (also see Sections 2.3.1 and 2.3.2) (Kesteven 2007; Norris 2017; Sun et al. 2022). With the newer surveys, larger collecting areas and

15 https://www.skao.int/en/explore/big-data
wider bandwidths means they are subject to suffering from more RFI. Frequency bands are reserved for different purposes, though with the search for Doppler-shifted spectral lines, there is sometimes a need to go outside the allocated areas. Added to this there is an increasing pressure from outside organisations for access to areas reserved for radio astronomy. Recently the communications industry has begun to establish their satellite constellations. Not only do these large satellite configurations present challenges to optical astronomy, but they pose additional complications to radio astronomy (IAU 2021). RFI can be dealt with in various ways both proactively and reactively. Through the regulation of reserved spectral bands and using radio-quiet zones some protection from RFI will be provided. However, these methods are not very effective against satellites and airborne radar (Kesteven 2007; IAU 2021). The observatory equipment can also be protected from transmitting any RFI. There have been recent developments in techniques of data manipulation to recognise and remove RFI (e.g., Sun et al. 2022).

For many of the science goals redshifts are needed. These can be obtained by comparison with optical/infrared (IR) surveys through a process called cross-identification. Due to the number of sources in modern surveys, spectroscopic redshifts are impractical and photometric redshifts have to be employed as well. For galaxies and AGN, photometric redshifts have a high accuracy up to $z \sim 2$. However, this is reliant on deep near-IR and multiband optical data. Not having these high-quality data prevents many surveys from obtaining good photometric redshifts and presents an ongoing challenge (Smith et al. 2016; Duncan et al. 2019; Williams et al. 2019; Asorey & Parkinson 2020). The determination of redshifts is important for investigating intrinsic properties of sources such as physical size and luminosity.

1.11.1 The Challenge with Optical Cross-Identification

As mentioned previously, redshifts are crucial to many of the scientific aims of radio continuum surveys, and they are often obtained through a process of cross-identification with optical/IR catalogues. Cross-identification is not an exact science and has been improving over the years. As survey sizes increase and the number of source detections grows, there need to be automated methods for host identification and characterisation of sources. As such, there
are a variety of different techniques that have been successfully employed to find host galaxies.

For example, the nearest neighbour technique has been used to cross-compare catalogues with a range of resolutions. This method is a proximity search. It is trying to locate the closest possible source and may include additional information such as magnitude and colour to weight the decision-making process (Kimball & Ivezić 2008). However, this method can be impractical for radio surveys. The extended radio emission and low resolution may lead to positional inaccuracies. This can be compounded with the large number of sources in the optical and IR catalogues, leading to multiple potential matches. Nearest neighbour is not necessarily a reliable way to find a potential match (Kondapally et al. 2021).

Other statistical methods have also been implemented. Downes et al. (1986) take a simplified approach by considering the Poisson probability of the counter problem. They calculate the extreme probabilities of the existence of possible counterparts over a given magnitude and over a given radius away from a radio source.

Fan et al. (2015) use a Bayesian approach to match point source counterparts to radio sources that are considered to have realistic morphology. These are sources with up to two lobes and/or a core in a relatively straight formation. This is a simple way of introducing morphology into cross-identification.

Most commonly in recent works, a likelihood ratio (LR) is used. This is a statistical calculation which considers the distance, magnitude and colour when determining the probability that an optical/IR source is the host counterpart to a radio source (Richter 1975; Sutherland & Saunders 1992; Smith et al. 2011; Fleuren et al. 2012; McAlpine et al. 2012; Williams et al. 2019; Kondapally et al. 2021). The LR formula (see Section 1.11.1) is the ratio of the probability of the source being a true counterpart to it being a random source, and is given by:

\[
LR = \frac{q(m,c)f(r)}{n(m,c)},
\]

where \(f(r)\) is the separation probability distribution, \(q(m,c)\) is the a priori probability that a radio source has a counterpart of magnitude, \(m\), and colour, \(c\), and \(n(m,c)\) is the sky density per unit (typically arcsecond\(^2\)) of objects at this magnitude and colour (Sutherland & Saunders 1992; Williams et al. 2019). A major limitation of the LR method is its poor performance for extended and
complex radio sources (Pineau et al. 2016; Kondapally et al. 2021). This issue is further compounded with how source finding algorithms deal with differing morphologies. They may split larger sources into smaller components or incorrectly group multiple small sources together (Williams et al. 2019, Kondapally et al. 2021). To match hosts to these sources, and to either group them or separate them, often a manual, visual inspection occurs. With much larger survey sizes this has to occur at much larger scales, for example LOFAR Galaxy Zoo (see Section 2.1.4.4) (Williams et al. 2019). This is time consuming and demonstrates a need for automated methods which can cross-identify extended sources better. These association of sources and host cross-identification hugely increases the value of the data and catalogues to the broader community.

These challenges, and my work to mitigate them, will be discussed further in Chapters 3 and 4.
1.12 SUMMARY AND SCIENCE OBJECTIVES

In Chapter 1 I have introduced radio galaxies, including their different morphological classifications such as the FRI/FRII classes (see Sections 1.4.1 and 1.4.2). Along with this I have introduced radio telescopes and surveys. I have presented a brief history before highlighting some of the current and upcoming instruments, building the background for Chapter 2 which has a focus on those telescopes, surveys and datasets required for this thesis. The life cycle of radio galaxies (Section 1.6), and the current challenges faced by radio surveys (Section 1.11) have been discussed in detail as they are crucial to the work that follows.

My thesis aims to explore extended radio galaxies using LOFAR. As described in Section 1.3 and given in more detail in Section 2.1, LOFAR is an ideal telescope for observing extended emission due to it being a low-frequency array with a comparatively high resolution and good sensitivity. The LOFAR Two-metre Sky Survey (LoTSS) is a full northern sky survey providing a large data set of sources to work with.

I started by using the innovative method of ridgelines to tackle one of the 'largest' problems in radio surveys: that of cross-identification for extended sources. For LoTSS DR1 a likelihood ratio (LR) method was used, and for those sources too large or complex for it to work, the citizen science project LOFAR Galaxy Zoo (LGZ) was used. The aim was to see if ridgelines can be used to provide successful host galaxy classifications, in an automated method that is comparable to LGZ.

Chapter 3 discusses my initial work with RL-XID. This includes setting up the trial data set and optimising the basic code so that it can successfully draw ridgelines on a majority of the trial sample. The work in Chapter 3 aims to find the best possible trial data set and prepare the basic code for cross-identification.

The application of RL-XID on the trial data set to test the potential of the ridgeline method for cross-identification and morphological classification is the focus of Chapter 4. The work in this chapter centres on whether or not RL-XID can provide correctly identified host galaxies on the trial DR1 data set when compared to LGZ. This is then extended to the whole of the LoTSS DR1 AGN
sample, to see how well it performs on sources of varying flux and sizes. This chapter also includes insight as to whether ridgelines have the potential to be used for automated morphological classification.

In the first part of my thesis I focused on the important work of successful cross-identification finding the host galaxies of radio sources, which helps determine intrinsic properties such as redshift, size, and luminosity. It is with successful cross-identification that further science questions surrounding radio galaxy populations can be explored. Looking at populations of radio galaxies helps us to understand their evolution and build better population models.

In Chapter 5 I move on to a scientific study of one of the radio galaxy populations. Here I use new observations to investigate a sample of 19 LoTSS-selected radio galaxies from the population of low luminosity FRIIs revealed by Mingo et al. (2019). New 1.5 GHz images of this sample of FRII-lows have been produced as described in Chapter 2. The aim of this chapter is to investigate any significant differences in morphologies between the low luminosity FRIIs and the traditional population of high luminosity FRIIs, and to explore the possibility of a higher abundance of older, fading sources present in the population.

Chapter 6 introduces the smaller projects as part of my thesis that have been on-going throughout my work. These include further adapting and optimising RL-XID for use with LoTSS DR2. This further demonstrates its capacity for adaptation, and the significance of its role in LoTSS DR2 alongside LGZ. Work is on-going to combine RL-XID with other automated methods to help reduce the dependence on LGZ in future data releases. This chapter also discusses the prospective avenues that both RL-XID and the FRII-low population have for future work.

Chapter 7 brings together the outcomes of each chapter and summarises the overall conclusions of the thesis.
2 Datasets and Data Processing

"In times of crisis, the wise build bridges while the foolish build barriers.”

T’Challa,
Marvel’s, Black Panther

This thesis is based on the analysis of radio images and catalogue data. The main instruments I have used are the LOw Frequency ARray (LOFAR, van Haarlem et al. 2013) and the Karl G. Jansky Very Large Array (VLA, e.g., Kellermann et al. 2020). These have been complemented with images from MeerKAT (e.g., Jonas & MeerKAT Team 2016), and optical and infrared data from large public catalogues such as Pan-STARRS (Chambers et al. 2019) and AllWISE (Cutri et al. 2013). The aim of this chapter is to introduce the data and some of the main techniques used throughout my thesis.

LOFAR and the VLA are telescope arrays, obtaining images through radio interferometry. This technique is described in detail in Section 1.7, which began to demonstrate why LOFAR is pushing the boundaries with low-frequency radio surveys.

To help place LOFAR and the VLA in the context of other radio telescopes, a brief history of radio instruments and surveys was given in Section 1.8, along with an overview on some of their contemporary counterparts in Section 1.9. In Sections 2.1 to 2.4 I discuss LOFAR and the LOFAR Two-metre Sky Survey (LoTSS), the VLA, and MeerKAT. This includes a comparison of how the images I use from LoTSS compare to the other surveys discussed in Chapter 1.

Although I did not produce the LoTSS images I have used, I have summarised how they were produced in Section 2.1.3. For these LoTSS images, a major element of this thesis work is the development of a new image analysis software, called RL-XID. This software analyses the images, using the highest flux values in an extended radio galaxy to trace the pathway of fluid flow through the jet. This pathway is known as a ridgeline; see Chapter 3.
statistical likelihood is then calculated on the neighbouring optical sources to the ridgeline to assess the probability of them being the host galaxy to the extended radio source. This matching of optical galaxies to radio sources is known as cross-identification, and is one of the challenges faced by newer, larger radio surveys (see Section 1.11). Tackling this problem and describing the development of RL-XID in detail are the focus of Chapters 3 and 4.

The second major element of the thesis is based on a set of new VLA observations that were obtained for a population of low-luminosity FRIIs discovered in LoTSS DR1 by Mingo et al. (2019). A sample of 19 sources were selected and observed using the VLA. In Section 2.3 I describe how I reduced, calibrated, and imaged the data, whilst Chapter 5 focuses on their scientific analysis.

The instruments, surveys and methods described in the chapter make up the building blocks required for my work in this thesis.
2.1 THE LOFAR TELESCOPE AND SURVEYS

A substantial amount of the work in this thesis involves using radio images from the LOw Frequency ARray (LOFAR). As has been previously described in Section 1.7, LOFAR is an array rather than a single dish telescope, split into three different types of antenna station\textsuperscript{16,17}. Currently there are 38 antenna stations in the Netherlands. The 24 core stations are packed into a 2 km area \textasciitilde 30 km from Dwingeloo. Around these, spread across the Netherlands out to \textasciitilde 100 km, are the 16 remote stations. These are arranged in an approximate logarithmic spiral, space and infrastructure allowing. The international stations include an additional six stations in Germany, three in Poland, and one in each of France, Ireland, Latvia, Sweden and the United Kingdom, with future stations planned in Italy and other countries\textsuperscript{17} (Heald et al. 2011; Stappers et al. 2011; van Haarlem et al. 2013). Each station acts like a single dish within an interferometric radio telescope, and each station has its own computing resources, meaning each station is a radio telescope in its own right (e.g., Stappers et al. 2011; van Haarlem et al. 2013). The international stations increase the longest baseline out to \textasciitilde 2000 km, between Ireland and Poland.

Using the stations in the Netherlands achieves images with a resolution of 6 arcseconds at 150 MHz, but with the inclusion of the international baselines this can be improved to a resolution of \textasciitilde 0.3 arcseconds. This is considerably better than any current or planned low-frequency radio telescope (Morabito et al. 2022).

Each station consists of low-band antennas (LBA) and high-band antennas (HBA). The specific number of each varies depending on the type of station. This allows LOFAR to have a frequency bandwidth of 10 MHz to 240 MHz, with the antennas optimised in the ranges of 30 – 80 MHz and 120 – 240 MHz\textsuperscript{18,19} (van Haarlem et al. 2013). It is the largest radio telescope observing at these low frequencies.

\textsuperscript{17} https://science.astron.nl/telescopes/lofar/lofar-system-overview/technical-specification/lofar-array-configuration/
\textsuperscript{18} https://science.astron.nl/telescopes/lofar/lofar-system-overview/technical-specification/lofar-stations/
\textsuperscript{19} https://science.astron.nl/telescopes/lofar/lofar-system-overview/technical-specification/antennas/
2.1.1 **LOFAR Two-metre Sky Survey (LoTSS)**

The reason for building any telescope, especially one like LOFAR, is to advance science beyond the current boundaries. This can be achieved through the many research areas covered by the surveys conducted with the telescope. These areas include the high-redshift Universe, where LOFAR can detect sources at \( z > 6 \), galaxy clusters at \( z > 0.6 \), active galactic nuclei, star forming galaxies, gravitational lensing, Galactic radio emission, cosmological studies, magnetic fields, radio transients, and recombination lines (see Shimwell et al. 2017, 2019 and references within). The aim of LOFAR is to be able to achieve these science goals by conducting wide and deep surveys at low radio frequencies.

The LOFAR extragalactic surveys were designed to have three tiers of observations. Tier 1 is the widest tier, covering \( 2 \pi \) steradians of the northern hemisphere, and includes both the LBA and the HBA. The HBA survey in Tier 1 is the LOFAR Two-metre Sky Survey (LoTSS). LoTSS covers a frequency range of 120 to 168 MHz (centred at 144 MHz). It is complemented by the wide area LBA survey, the LOFAR Low-band Sky Survey (LoLSS) at 42 – 66 MHz (de Gasperin et al. 2021). Tiers 2 and 3 are deeper and cover smaller sky areas; these are the LoTSS and LoLSS deep fields (Shimwell et al. 2017; Kondapally et al. 2021; Tasse et al. 2021). These are deeper surveys across smaller sky areas, and targets of interest (see Shimwell et al. 2022 and references within).

In the first data release from LoTSS the final catalogue was made from the 120 – 168 MHz continuum images and contains \(~320,000\) sources from 424 deg\(^2\) of the Northern hemisphere. These are 6 arcsec resolution images (giving 1 pixel \( \approx 1.5\) arcsec) with a median sensitivity of \( 71 \mu\)Jy beam\(^{-1}\), an astrometric uncertainty of \(~0.2\) arcsec, and an uncertainty on the flux density of \(~20\%) (Shimwell et al. 2019).

LoTSS data release 2 covers 27\% of the Northern sky, or 5634 deg\(^2\). DR2 contains \(~4.4\) million sources imaged at 6 arcsec resolution, with a median sensitivity < \( 100 \mu\)Jy beam\(^{-1}\). In my thesis I use a combination of the DR1 catalogue (see Section 2.1.4) and the DR2 images (see Section 2.1.3). These have a greater recovery of unmodelled emission and a dynamic range (the ratio of the peak flux to the off-source RMS) up to a factor of four times better than DR1. The uncertainty on the flux density scale has also been improved to \(~5\%) (Shimwell et al. 2022).
2.1.2 A COMPARISON OF LoTSS TO OTHER RADIO SURVEYS

It is important to understand how LoTSS compares to both long-standing (see Section 1.8) and newer surveys (see Section 1.9).

There are contemporary surveys LoTSS could be compared to, such as the Multifrequency Snapshot Sky Survey (MSSS, Heald et al. 2015), the Evolutionary Map of the Universe (EMU, Norris et al. 2011), POlarization Sky Survey of the Universe’s Magnetism (POSSUM, Gaensler et al. 2010), APERture Tile In Focus survey (APERTIF survey, Adams et al. 2022), GaLactic and Extragalactic All-sky MWA – survey eXTended (GLEAM-X, Hurley-Walker et al. 2022), the Karl G. Jansky VLA Sky Survey (VLASS, Lacy et al. 2020), and the Global Magneto-Ionic Medium Survey (GMIMS, Wolleben et al. 2019, 2021). However, they are either lower resolution or lower sensitivity, so LoTSS is pushing into new territory and will be competitive even into the age of the SKA.

Figure 2-1 – The same 1 deg² demonstrating the difference between sensitivity and resolution to extended structures between LoTSS DR1 and NVSS, FIRST, and TGSS. Image from J. H. Croston.
The various parameters of a survey all play a part in the differing quality of images produced. Combinations of factors such as sensitivity, resolution, and frequency will mean that different surveys will be well matched to different science goals. With its combination of low-frequency, high sensitivity, and high resolution LoTSS is ideally suited to studying the extended structures of radio galaxies. This is demonstrated in Figure 2-1 where the image quality of the same 1 deg² in LoTSS (LOFAR Tier-1) is compared to NVSS, FIRST, and TGSS. Here NVSS can detect the extended structure without any of the more compact structure details, whereas FIRST can detect the smaller scale structure without the extended emission. TGSS produces an image with both components but lacks the detail seen in LoTSS (LOFAR Tier-1).

Figure 2-2 – A comparison of sensitivity, frequency, and resolution of established and new/upcoming surveys. The width of the circle represents the resolutions of the survey, and the horizontal bar denotes the bandwidth of the survey where it covers a range of frequencies. The green, blue and red lines represent the equivalent sensitivity to LoTSS for sources with spectral indices of -0.7, -1.0 and -1.5 respectively. Image from Shimwell et al. (2019).
As can be seen in Figure 2-2, LoTSS has a sensitivity which exceeds that of the established wide-area higher frequency surveys discussed earlier: WENSS, SUMSS, NVSS and FIRST. As such the source density of LoTSS far exceeds these surveys (> 8 times), as well as current low-frequency surveys such as VLSSr, MSSS, TGSS-ADR1, GLEAM and LoLSS. Whilst pushing the boundaries of current low-frequency surveys, LoTSS is comparable to the newer and upcoming high-frequency surveys such as EMU.

Table 2-1 summarises the main features of these surveys giving their resolution, RMS, frequency, and sky area. It can be seen, for example, that the APERTIF images (Röttgering et al. 2011; Kutkin et al. 2022) complement EMU (Norris et al. 2011) very well. EMU will chart everything south of $\delta = 30^\circ$ to a similar depth as APERTIF. Likewise, the GLEAM-X survey is the southern complement to LOFAR’s Multifrequency Snapshot Sky Survey (MSSS), which has a similar sensitivity and angular resolution (Heald et al. 2015; Hurley-Walker et al. 2017).
Table 2-1 – The resolution, RMS, frequency and sky area of the surveys discussed in Sections 1.8 and 1.9, compared to the LOFAR surveys (bold). In particular, is the LoTSS survey discussed in Section 2.1.1 (Becker et al. 1995 (FIRST); Rengelink et al. 1997 (WENSS); Best et al. 2003 (NVSS); Mauch et al. 2003 (SUMSS); Kimball & Ivezić 2008 (FIRST, NVSS, WENSS); Röttgering et al. 2011 (APERTIF); Lane et al. 2014 (VLSSr); Heald et al. 2015 (MSSS); Jarvis et al. 2016 (MIGHTEE); Hurley-Walker et al. 2017 (GLEAM-X); Intema et al. 2017 (TGSS-ADR1); Shimwell et al. 2019 (LoTSS); McConnell et al. 2020 (RACS); Norris et al. 2021 (EMU); Kutkin et al. 2022 (APERTIF); [https://science.nrao.edu/vlass](https://science.nrao.edu/vlass) (VLASS)).

<table>
<thead>
<tr>
<th>SURVEY</th>
<th>RESOLUTION (arcsec)</th>
<th>NOISE (mJy/beam)</th>
<th>FREQUENCY (MHz)</th>
<th>AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREVIOUS GENERATION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIRST</td>
<td>5</td>
<td>0.15</td>
<td>1400</td>
<td>b &gt; 30°¹</td>
</tr>
<tr>
<td>NVSS</td>
<td>45</td>
<td>0.45</td>
<td>1400</td>
<td>δ &gt; -40°</td>
</tr>
<tr>
<td>SUMSS</td>
<td>43</td>
<td>10</td>
<td>843</td>
<td>δ &lt; -30°</td>
</tr>
<tr>
<td>WENSS</td>
<td>54</td>
<td>18</td>
<td>325</td>
<td>δ &gt; 30°</td>
</tr>
<tr>
<td>HIGH FREQUENCY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMU (Pilot)</td>
<td>13</td>
<td>0.0175</td>
<td>944</td>
<td>δ &lt; 30°</td>
</tr>
<tr>
<td>RACS (DR1)</td>
<td>15 - 25</td>
<td>0.2 - 0.4</td>
<td>887.5</td>
<td>δ &lt; 41°</td>
</tr>
<tr>
<td>MIGHTEE</td>
<td>6</td>
<td>0.001</td>
<td>900 - 1670</td>
<td>δ &gt; -41°</td>
</tr>
<tr>
<td>VLASS</td>
<td>2.5</td>
<td>0.07</td>
<td>2000 – 4000</td>
<td>δ &gt; -40°</td>
</tr>
<tr>
<td>APERTIF</td>
<td>10</td>
<td>0.02</td>
<td>1355</td>
<td>δ &gt; 0°</td>
</tr>
<tr>
<td>LOW FREQUENCY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLEAM-X</td>
<td>120 – 45</td>
<td>1.27</td>
<td>72 – 231</td>
<td>δ &lt; 30°</td>
</tr>
<tr>
<td>LoLSS</td>
<td>15</td>
<td>1</td>
<td>40 – 70</td>
<td>δ &gt; 0°</td>
</tr>
<tr>
<td>MSSSS HBA</td>
<td>120</td>
<td>10</td>
<td>119 – 158</td>
<td>δ &gt; 0°</td>
</tr>
<tr>
<td>MSSSS LBA</td>
<td>150</td>
<td>50</td>
<td>30 – 78</td>
<td>δ &gt; 0°</td>
</tr>
<tr>
<td>TGSS-ADR1</td>
<td>25</td>
<td>3.5</td>
<td>147.5</td>
<td>δ &gt; -53°</td>
</tr>
<tr>
<td>VLSSr</td>
<td>75</td>
<td>100</td>
<td>73 – 74.6</td>
<td>δ &gt; -30°</td>
</tr>
<tr>
<td>LoTSS</td>
<td>6</td>
<td>0.1</td>
<td>120 – 168</td>
<td>δ &gt; 0°</td>
</tr>
</tbody>
</table>

¹Covers the North and South Galactic caps.
²Covers the four fields COSMOS, XMM-LSS, ECDFS and ELAIS-S1.
Between Figure 2-2 and Table 2-1 it can clearly be seen that LoTSS has achieved a depth, area, resolution, and sensitivity previously unobtained, and is ~2 – 3 orders of magnitude better than any existing low-frequency survey (van Haarlem et al. 2013; Shimwell et al. 2017), as well as being 50 – 1000 times more sensitive and 5 – 30 times higher in resolution (Shimwell et al. 2017). When comparing to higher-frequency surveys LoTSS has a matching resolution to FIRST and will eventually cover a wider area to a much greater depth. VLASS will not survey as deeply and is less sensitive to extended structure because it only uses one configuration of the VLA, but it does have images with a resolution of 2.5 arcsec to pinpoint the precise location of sources (Shimwell et al. 2017; Lacy et al. 2019).

Whilst comparing surveys it is worth taking a moment to discuss how the SKA fits within the current suite of telescopes on offer, I will compare the SKA to the upgraded VLA (see Section 2.2) and LOFAR (see Section 2.1) which are the main datasets I am using. Compared to the VLA, the SKA-Mid will survey the sky about 60 times faster, with a resolution that is four times better and a sensitivity increase of five times\(^2\). In comparison to the current LOFAR surveys the SKA-Low will be able to survey the sky 135 times faster, with 25% better resolution and eight times better sensitivity\(^2\). However, even the deepest SKA-low surveys are confusion limited. The deeper surveys go, there is a higher number of faint background sources that are above the detection limit, and when the angular resolution is low, more of these sources cannot be resolved. This means they blur together to make additional background noise on top of any thermal or artifact related noise already present. The addition of the international baselines to LOFAR and the new stations coming online shortly, such as the one in Italy, will improve the low-frequency sensitivity, \(uv\) – coverage, and resolution even further, and no other instrument with these capabilities is planned, including the SKA (Morabito et al. 2022)

\(^2\) [https://www.skao.int/en/explore/telescopes/ska-mid](https://www.skao.int/en/explore/telescopes/ska-mid)

\(^2\) [https://www.skao.int/en/explore/telescopes/ska-low](https://www.skao.int/en/explore/telescopes/ska-low)
2.1.3 **The LOFAR pipeline**

During my thesis I used mosaics and images from LoTSS DR2 covering the DR1 sky area. These 6 arcsec resolution images are produced from the ~7.5Pb of raw data covering around 5500 deg². As the LOFAR Surveys team have an established pipeline for data processing and image production there was no need for me to reproduce the LoTSS images as part of the thesis work. For a full description of the processes and software used by the Surveys team see Shimwell et al. (2019, 2022) and Tasse et al. (2021) (and references within).

For DR2, the direction-independent calibration process is the same as DR1. The direction-independent effects are those which affect all the directions on the sky equally and are differences such as the clock offsets between each station, ionospheric Faraday rotation, and amplitude calibration. All of these effects are described in detail by de Gasperin et al. (2019). The calibration process is described by van Weeren et al. (2016) and Williams et al. (2016) and it uses the LOFAR Default Pre-processing Pipeline (van Diepen et al. 2018) and Black Board Selfcal (Pandey et al. 2009). The data are calibrated using a calibrator model which is consistent with Scaife & Heald (2012). This has a flux density scale accurate within ~5% of the Perley & Butler (2017) scale (used with the VLA observations, see Section 2.3.3.2).

This is followed by the direction-dependent calibration and imaging. The direction-dependent effects are those that alter the gains in differing ways for different positions of the sky. They are particularly ionospheric effects, and errors in the station beam model (differences in the response of the station). These are severe in low-frequency datasets, making the process complicated. For the full details of the original DR1 direction-dependent pipeline see Shimwell et al. (2019) Section 2.3, and Tasse et al. (2021) Section 3 for the improved calibration for DR2. Here, the direction-dependent calibration is applied during the imaging process using the same software packages as DR1. The DR2 images have a few improvements from the DR1 images. In the first instance there is an improvement in dynamic range (up to a factor of four times better) and the fidelity of faint diffuse emission. As there is now an additional post-processing step to refine the flux density, the uncertainty on this has improved from ~20% to ~5%. There is also a slight improvement in the astrometric uncertainty, but it is still ~0.2 arcsec.
The calibration and imaging process for LoTSS is very different to the one I describe in Section 2.3 for the VLA observations. As described by Shimwell et al. (2019, 2022) the pipeline is a repeated process of imaging and calibration. This is done firstly to divide the map into smaller mosaics, and then to apply different phase and amplitude calibrations with further improved models at each stage. My observations are focused on a single target in a smaller area. I have manually removed much of the RFI that is removed automatically in the LoTSS pipeline. My calibration steps also only involve one iteration of each of the calibration processes. These iterations in the LoTSS pipeline act as the self-calibration steps for their images. This was checked and carried out manually for the VLA images.

2.1.4 BUILDING THE LoTSS CATALOGUE

In this thesis I make use of the LoTSS DR1 catalogues and the DR2 images. (Shimwell et al. 2019; Williams et al. 2019). In the course of the work reported in Chapters 3 and 4 I make use of three different catalogues:

(i) The DR1 radio source catalogue released by Shimwell et al. (2019)
(ii) The value added DR1 catalogue which includes host identifications and source associations released by Williams et al. (2019), with redshifts obtained by Duncan et al. (2019)
(iii) The parent catalogue of potential optical and infrared host galaxies that was used by Williams et al. (2019) in their optical identification process

In the sections below I briefly summarise how these catalogues were constructed.

2.1.4.1 Source finding

For both data releases the shape and sizes of the sources were obtained and catalogued using the Python source detection code, PyBDSF (Mohan & Rafferty 2015). PyBDSF finds the Gaussian components in each mosaic, and some of these components may need to be associated. This means to bring them together as components of a single, extended source. The Gaussian components do not form a clean catalogue of sources. Components that are a mix of nearby, distinct sources, are known as ‘blended’ sources, components
that are physically associated, but have been catalogued as individual entries because of the lack of continuous emission need to be reassociated, and some components are artefacts or spurious emission. The released radio catalogue is the outcome of the PyBDSF process described here.

2.1.4.2 Parent optical/IR catalogue for host galaxy identification

The parent optical/IR catalogue used by Williams et al. (2019) was created using the method described in Section 4.2.1 of their paper. They implement a likelihood ratio to match sources between the host galaxy counterparts in Pan-STARRS and AllWISE, and the final LoTSS DR1 radio catalogue. For some large optical galaxies Williams et al. (2019) also make use of the Sloan Digital Sky Survey (SDSS) DR-12 catalogue (Alam et al. 2015), and the extended sources catalogue (2MASX, Jarrett et al. 2000) from the Two Micron All Sky Survey (2MASS, Skrutskie et al. 2006). The Pan-STARRS 3π survey (Chambers et al. 2019) has a 5σ magnitude limit in the stacked grizy images of 23.3, 23.2, 23.1, 22.3 and 21.4 magnitude. It covers the entire sky north of δ = 30°. For Pan-STARRS the typical point spread function (PSF) is around 1 – 1.3 arcsec. The AllWISE catalogue (Cutri et al. 2013) has photometry for more than 747 million sources across the full sky. These are in the 3.4, 4.6, 12 and 22 μm (W1, W2, W3 and W4) bands, with the W1 and W2 bands having significantly better sensitivity and a typical PSF of 6 – 6.5 arcsec.

The focus of Chapters 3 and 4 is on the ridgeline drawing process and the cross-identification of optical host galaxies for extended radio sources. The work in Chapter 4 focuses on data from the parent optical/IR catalogue using the i-band data from Pan-STARRS and W1-band from AllWISE as well as the colour generated from i - W1. All magnitudes are in the AB system (Oke & Gunn, 1983) unless otherwise stated.

2.1.4.3 Optical host cross-identification

In LoTSS DR1, 73% of the 318,520 sources have optical counterparts, and these were generated in two ways (Williams et al. 2019). For LoTSS DR1, Williams et al. (2019) used a decision tree to select which sources were to be associated and to have their optical hosts determined automatically, and which went to
visual classification with LOFAR Galaxy Zoo (See Section 2.1.4.4). The large and bright radio sources, most likely to require visual classification, were defined to have a major axis >15 arcsec and flux density >10 mJy. Those sources smaller than 15 arcsec with nearby companions were considered as possible unassociated components of complex sources and were inspected again before being sent to LGZ for visual classification, as described in the next section. In the final catalogue, 94% of the optical hosts were successfully found using a likelihood ratio method that forms the basis behind the work in Chapter 4. Of the remaining extended radio sources ~12,000 went to LGZ for visual identification. The aim of the work in Chapters 3 and 4 is to generate an effective method by which the number of sources that need cross-identification through LGZ is reduced, hence lowering the amount of time, resources, and chance of human error.

2.1.4.4 LOFAR Galaxy Zoo

The LoTSS DR1 value-added catalogue (Williams et al. (2019) includes a large set of extended radio sources that have been associated and cross-identified using the LOFAR Galaxy Zoo (LGZ)22 citizen science approach, built on the Zooniverse platform. The details of the LGZ images and process are given in detail by Williams et al. (2019). The volunteers are shown three panels of each extended source that they are able to flip through with ease (see Figure 2-3). The process is designed to identify host galaxies of extended radio sources, to filter for any complex structures, and to ensure that all components of a radio source are matched with each other. Here volunteers were asked to select the possible hosts and associated components of a radio source, as well as flag any instances where a source might need to be checked further.

Although a citizen science approach was used for DR1, the classifications were performed by experts in the field, which is likely to have improved the reliability of the results. For DR2 a similar project is in progress, but available to the public (Hardcastle et al. in prep.). In Chapter 4 I compare the results of my likelihood ratio to those of LGZ. In this work, I therefore adopt the DR1 LGZ identifications as the truth set used for comparing my results. Therefore, the truth set of hosts is based on a requirement of greater than 2/3 agreement between volunteers, as described by Williams et al. (2019). I have further tested the reliability of the LGZ truth set by examining the subset of my sample

22 https://www.zooniverse.org/projects/mjh22/lofar-galaxy-zoo
of large, bright sources for which a compact FIRST source consistent with a radio core is present (62% of my sample), finding that for 97% of sources with a bright, compact FIRST source in a plausible host location, the LGZ host ID coincides with the FIRST core. This is not surprising, as the FIRST contours were available as part of the LGZ visual process. I am therefore confident that it forms a useful truth set that represents the state of the art in host identification for large extended source samples, and so provides the best testing ground for my method.

![Figure 2-3](image)

Figure 2-3 – The three panels from the LOFAR galaxy zoo interface. *Left*: Pan-STARRS colour image overlaid with LoTSS (yellow contours) and FIRST (green contours); *middle*: Pan-STARRS colour images overlaid with Pan-STARRS (x) and WISE (+) sources; *right*: WISE W1-band colour image overlaid with the LoTSS and FIRST contours. Image from Williams et al. (2019).

I note that the LGZ catalogue is not perfect, with a small number of source matches resulting in incorrect IDs. As discussed in Section 6.1.1, optimising the method for elimination of sources with no valid host is the subject of future work with the second data release of LoTSS.

The Williams et al. (2019) dataset includes fully associated components. It is important to remember that the problem of associating components is beyond the scope of this thesis. It is assumed this will be done by other means prior to the application of the methods in Chapters 3 and 4, although there is the potential of extending the use of ridgelines to this problem as well.

The final LoTSS DR1 catalogue has the combined host galaxy classifications from both the automated method and LGZ.
2.2 THE VLA OBSERVATIONS

The work I present in Chapter 5 is based on set of observations taken using the Karl G. Jansky Very Large Array (VLA). The new observations are briefly introduced in Section 2.2.1, with further details in Chapter 5. In Section 2.3 I explain the process I undertook to reduce this data and produce images. The VLA is an array of 27 antennas, each one is 25 m in size and they are arranged in a Y shape with a maximum baseline of ~36 km (Thompson et al. 1980; Napier et al. 1983; Perley et al. 2009, 2011; Kellermann et al. 2020). The VLA has been operational since 1980 and the extended VLA project completed its upgrade in 2011 to the Karl G. Jansky VLA, which greatly increased its sensitivity and dynamic range, as well as its image capture speed (Perley et al. 2009, 2011, Kellermann et al. 2020). It is able to observe across a wide range of frequencies from ~75 MHz up to ~50 GHz (Cohen et al. 2007, Perley et al. 2011).

The VLA has produced the flagship surveys NVSS and FIRST, discussed in Section 1.8, and more recently its major continuum survey at ~3 GHz is the VLA Sky Survey (VLASS) (e.g., Condon 2015, Lacy et al. 2019). VLASS will survey everything north of $\delta = -40^\circ$ and is expected to produce a catalogue of over 10 million sources at a resolution of 2.5 arcseconds (Condon 2015). In Chapter 5 I have used the quick look images as part of my analysis to compare my 1.5 GHz observations with 3 GHz images.

2.2.1 OBSERVATION DETAILS

Chapter 5 focuses on my work with a sample of low-luminosity FRIIs. A new set of VLA observations of a sample of 19 radio galaxies selected from the LoTSS survey (see Section 2.1.1) were obtained, and I reduced and analysed the data. The VLA observations were taken in the L-Band (1 – 2 GHz) over four observing sessions. The A configuration sessions were on August 10th, 2019, and August 31st, 2019, whilst the B configuration observations were taken on March 27th, 2019, and May 11th, 2019. All observations were part of the observing program 19A-151. Each session contains the flux density calibrator 3C286, the same four secondary calibrators, and two scans on the 19 targets. This gives a total of

23 https://science.nrao.edu/vlass/data-access/vlass-epoch-1-quick-look-users-guide
four scans of each target. The A configuration enables the sources to be mapped with a resolution of ~1.3 arcsec and was chosen for its potential to highlight hotspots in the sources. The B configuration, with a resolution of ~4.3 arcsec, complements this by emphasising more of the possible extended emission.

The processes I used to reduce the data and produce images are described in detail in Section 2.3. My focus was on the production of images in total intensity (Stokes I). The full polarisation data is available but has not yet been calibrated. The analysis is presented in Chapter 5 with the sample selection discussed in full in Section 5.2, along with the sample details. The final images are presented in Section 5.3.

### 2.3 VLA DATA PREPARATION

Data reduction must be carried out on the observation data before an image is produced. This process covers stages such as cleaning the data and calibrating the data before finally producing an image. To carry out the data reduction the Common Astronomy Software Applications Version 5.7.0-13424 (CASA, McMullin et al. 2007) created by the National Radio Astronomy Observatory (NRAO) was used, employing the methods and techniques described fully online in the CASA JVLA tutorials25. Any commands named and processes used are described in full in the CASA Cookbook26.

The recorded complex visibilities containing the information about the amplitude and phase (see Section 1.7) are stored as a measurement set, the default CASA file, which is a folder containing binary tables and acts as a relational database. Data reduction via CASA has several stages, each of which are described in full in the following sections:

- Initial data cleaning
- RFI flagging
- Calibration
- Image generation
- Self-calibration

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24 [https://casa.nrao.edu/](https://casa.nrao.edu/)
26 [https://casa.nrao.edu/casa_cookbook.pdf](https://casa.nrao.edu/casa_cookbook.pdf)
2.3.1 **INITIAL DATA CLEANING**

The dataset needs to be cleaned before it can be processed. Cleaning is the removal of any problematic data. Problematic data can be caused by technical or mechanical issues, or radio frequency interference (RFI). RFI consists of unwanted radio signals that interfere with radio observations and can mask the weaker signals. Typical sources of RFI include natural occurrences such as lightning and solar flares, and man-made origins like satellites and wireless computing networks. Even microwave ovens, mobile phones and garage door openers are strong enough to generate RFI. For this reason, radio telescopes are often built in isolated, radio quiet areas, and restrictions are placed on the use of certain frequency bands.

When cleaning the data, no datapoints are actually deleted or removed, they are just ‘flagged’ as unwanted and are no longer considered in any processes that follow. Two main commands are used to carry this out. `flagdata` allows the user to flag data in a variety of set methods, or to manually specify what is to be flagged, for example, antennas/baselines, spectral windows/frequency/channels, time ranges or fields/sources. These can be combined to produce as broad or specific flagging as needed. The use of `flagmanager` to save and restore flags means that the file can always be returned to a previous state. After each flagging and calibration stage the data was carefully manually checked to ensure no off-source data or RFI was left, particularly on the phase calibrator. To begin with the observation data is examined so any known technical or setup issues can be flagged before moving on to the removal of RFI.

2.3.1.1 **Data Setup**

There are two logs associated with the dataset: the observer log, and the output of `listobs`, which lists the details of each scan within the observation. The observer log can be checked for a variety of information about the observation, such as times of observation, weather conditions and antenna information. If any antennas have lost or corrupted data, it is recorded in the observer log. The output from `listobs` details the scans with the source, times, spectral windows used and identifiers, as well as which antennas were used and their identifiers to be used throughout the data processing procedure. The first couple of scans will be less than a minute long and are setup scans for the observation. Any
antennas identified as having lost or corrupted data during the observation, and any scans identified as setup can be safely flagged at the start of the process.

2.3.1.2 Shadowed antennas
Antenna shadowing is most likely to occur when sources are at a low elevation and the array is in a compact configuration. Shadowing is where an antenna’s line-of-sight is blocked (fully or partially) by another antenna in front of it. As the D configuration is most significantly affected by shadowing and my data is observed in the A and B configurations, this flagging was not carried out.

2.3.1.3 Clipping zero data
There are times when the correlator records zero-amplitude data. To flag this the zero-data are clipped.

2.3.1.4 Quacking
At the start of each scan the array takes time to settle. To allow for this movement at the beginning, 10 secs at the start of each scan are flagged. This is called quacking, and it removes the data at the scan boundaries for a specified period of time.

2.3.2 Flagging RFI
Having flagged any known issues, the dataset is then cleaned of any significant sources of RFI. RFI flagging falls into two broad categories: automated commands carried out through flagdata, and manual flagging.

The observation dataset across each of the frequency bandwidths is split into several spectral windows. Each of these spectral windows is then divided further into channels of set frequency width. When performing RFI flagging this can be extremely helpful as RFI may be restricted to specific spectral windows, or even channels within windows. Narrow-band RFI is where just a few channels are affected. If more than a few are affected then it is broad-band RFI. Using the observer’s log and plotms it is possible to determine if the RFI is continuous or
intermittent. The division of the data in this way makes it easier to determine the location of RFI in the data.

2.3.2.1 Hanning Smooth

The first of the automated steps is Hanning Smoothing. This removes the ringing effect from the Gibbs Phenomenon generated around strong RFI. It uses a triangular smoothing kernel (with a centre weighting of 0.5 and two edge weights of 0.25) as it carries out a running mean across the spectral axis. It reduces the Gibbs ringing at the cost of halving the spectral resolution.

2.3.2.2 Automatic flagging

There are two automated RFI flagging algorithms designed to find and remove the majority of RFI in the observation data. Both of these function use a 4σ cut-off for the time deviations and 3σ for frequency.

\texttt{tfcrop}

This autoflag algorithm operates on uncalibrated data, iterates through segments of time, and looks per scan, per baseline, per spectral window, per polarisation for RFI. It has four stages: detecting short duration RFI, searching for time persistent RFI, searching for time persistent, narrow-band RFI and searching for low-level wings of strong RFI. This command is run twice to allow for deeper flagging and to cover both the parallel and cross-hand correlations.

\texttt{rflag}

This autoflag command needs a bandpass calibration first. To run this a preliminary calibration is performed and applied to the calibrator before flagging the RFI. This algorithm also iterates through time and uses a statistical filter on the data.

2.3.2.3 Manual flagging

Once the automated flagging procedures have removed most of the RFI the observation data can be inspected for remaining problematic data and this can be manually flagged. The dataset is inspected using \texttt{plotms} in a variety of ways to find any remaining RFI. Once any problematic data has been identified it can
be flagged in two ways: either through interactive selection in the `plotms` interface, or by using the manual flagging capacity in the `flagdata` command. Throughout the following calibration stage `plotms` and `flagdata` are used continuously to check that each stage has worked successfully, and to flag out any difficult data found.

The observation datasets are divided into 18 (0 – 17) spectral windows (SPWs) to help with removing RFI (see Section 1.7). For each of the four datasets SPWs 0 and 1 are setup scans and are flagged. SPWs 10 and 11 are well known for, and verified to, contain a high amount of RFI so were flagged from all datasets. The remaining SPWs in each calibrator were visually checked and either the SPW was flagged or, if the RFI was narrow, the channels within the SPW were flagged. Lastly, each source’s weights were checked, using `imstat`, to see if any SPW peaked with high weights indicating RFI present. If so, those SPWs were flagged. The most common SPWs to present with RFI were 3, 4, 5, 6, 16, and 17. This means that for each source between ~ 40 – 60% of the data was flagged.

### 2.3.3 Calibration

Once the dataset appears as free of RFI as possible, calibration can begin. Calibration corrects for effects that alter the response of the instrument and recorded measurements from an idealised situation. These might be instrumental, such as antenna position. For large arrays like the VLA and LOFAR which have many antennas all observing the same source at the same time, the antenna gain corrections are the small differences between the responses for a given signal. There can also be temporary local effects, for example the atmosphere can cause shifts in the phase of an observed source.

Calibration can mean the steps that are taken to ensure the instrumentation is operating correctly, and those procedures carried out post observation. These steps determine the correction factors that must be applied to each target scan to make them as close as possible to what an idealised interferometer would measure. These are calculated from the calibrators and then applied to the target scans so that when the dataset is imaged an accurate picture of the sky is obtained. This is a series of tasks generating cumulative calibration tables to correct for each effect. These tables must then be applied to the data using `applycal` to create the ‘corrected’ data.
Further calibration can occur at a later stage. This is known as self-calibration and is described in Section 2.3.5. The process of calibration is set out in Section 2.3.3.2 and follows the procedures laid out in the VLA tutorials\textsuperscript{27,28}.

### 2.3.3.1 Primary and secondary calibrators

The standard procedure for calibrating an observation is to start by calibrating the flux density (or primary) calibrator and then apply these corrections to the (complex) gain (or secondary) calibrators. Therefore, each observation must include a primary calibrator for which the flux density is steady and known, and nearby secondary calibrators which can be observed both before and after the target sources. The secondary calibrators may have a flux that varies, which will stop them from being primary calibrators. Their intrinsic phase needs to be considered constant over the whole observation. They need to be unresolved (point) sources of radiation, or resolved provided a model is available. These secondary calibrators are within a small angular offset on the sky, so that the radiation path through the atmosphere to the telescope is as similar as possible, and it can be assumed that any corrections affecting the calibrator will necessarily need to be applied to the target.

My observations contain multiple target sources and therefore make it necessary to have multiple secondary calibrators. Repeated scans of the targets were taken at different times meaning the secondary calibrators must be observed both before and after in each different time slot to account for any environmental changes. This is not necessary for the primary calibrator, which is scanned only once, for a longer period, at the start or end of the observation session. If the primary calibrator is close enough to the target source it can also be used as a secondary calibrator, and therefore would need to be scanned again either side of the target.

In each of my observation data sets there are 19 target sources scanned twice with four secondary calibrators observed throughout the process in such a fashion that there are always one or two targets between each pair of scans on the same secondary calibrator. All targets are scanned between two secondary calibrators, and these are what are used to calibrate the target data.

\textsuperscript{27} https://casaguides.nrao.edu/index.php?title=VLA_Radio_galaxy_3C_129:_P-band_continuum_tutorial-CASAS.7.0
\textsuperscript{28} https://casaguides.nrao.edu/index.php?title=VLA_Continuum_Tutorial_3C391-CASA5.7.0
2.3.3.2 Calibration processes

Before the data can be calibrated properly, any light touch calibration carried out for the automated flagging must be removed. From here, the antenna calibration table needs to be set up, so it is generated first. To correctly match and combine all the signals in the data the exact location of each antenna at the time of the observation is needed.

Having generated the required initial calibration tables, they can be applied to the primary calibrator to produce further calibration tables to be applied to the secondary calibrators. Initially the flux calibrator is scaled using the Perley & Butler (2017) 3C286 model. When the calibration is applied to the secondary calibrators, they will be scaled to the flux calibrator. From here a starting phase calibration is carried out to average over any, typically small, variations in phase with time, before solving for the bandpass.

The next step is to solve for any antenna-based delays. For observations with the upgraded VLA these should be around 4 ns. With these tables it is then possible to carry out a bandpass calibration. The bandpass solution is considered to be constant for the observation. From here the amplitude and phase calibration is calculated for the primary calibrator, correcting for changes that occurred during the observation time. The calibration tables for the primary calibrator are then used to find the amplitude and phase corrections for the secondary calibrators. These are scaled using the known flux of the primary calibrator, this ensures a reliable flux scale.

Once all the calibrators are scaled and the tables with the corrections are generated, the calibration can be applied, first to the calibrators and then to the target sources. Having applied the calibration, the measurement sets were then weighted according to their noise levels using statwt and combined using concat. This was applied both to combining the observations of the same configurations and combining the different configurations together.
2.3.4 IMAGING

Once calibration is complete and has been applied to the source, and the measurement sets of the different configurations have been weighted and combined, the data can be imaged. CASA uses the CLEAN algorithm (Högbom 1974). Here the underlying process is to form a ‘dirty’ image by Fourier inversion of the data. The algorithm then works at iteratively removing the dirty beam pattern from the image using deconvolution. The full details on the process and the input parameters can be found in the VLA imaging tutorial\(^\text{29}\).

To generate images there are a few key parameters input into tclean that vary depending on aspects of the data such as observation band and configuration. As part of my analysis, I created images for both the A configuration and the B configuration to check that they were well calibrated, before proceeding to combine the datasets and generate images for the combined configurations.

The cell size parameter determines the number of arcseconds per pixel in the image. This is chosen in relation to the beam size, which is set by the observation band and configuration. For the L-Band in A configuration the beam width is 1.3 arcsec and for the B configuration it is 4.3 arcsec. It is typical to have 3 to 5 pixels per beamwidth, therefore for the combined images the cell size was chosen to be 0.4 arcsec. This complements the A configuration and oversamples the B configuration.

In conjunction with cell size is image size, which determines the size of the image to clean. If the chosen image size is too small there may be bright distant sources beyond the image area that cause artifacts across the image, leading the sources to need identifying and to be specified in the cleaning routine. I decided to clean over the whole primary beam (33 arcmin square image). At 0.4 arcsec per pixel this gives an image size of 4950 pixels.

I used a Briggs weighting with robust = 0. Certain visibilities are given more, or less, weight depending on their location in the \(uv\)-plane with this parameter. A robust = 2 is considered to be close to a ‘natural’ weighting which emphasises the shorter baselines and improves the surface brightness sensitivity. A robust = -2 is nearer to a ‘uniform’ weighting, which has more of an emphasis on the longer baselines and improves the resolution of the image. With a robust of 0

\(^{29}\) https://casaquides.nrao.edu/index.php?title=VLA_CASA_Imaging-CASA5.7.0
there was an improvement in the dynamic range of the images without loss of the hotspot detail.

The multiscale deconvolver was used (Cornwell 2008) with the scales set to $[0, 1x, 2x, 3.5\times\text{beam}]$ which, for the 1.3 arcsec resolution images gives values of $[0, 3.3, 6.5, 11.4]$. This was applied as the multiscale deconvolver is used for handling extended sources, and it is anticipated that these sources will have extended emission.

As these observations are performed in the lower frequencies, the wide-field imaging parameter ($w$-projection) must be applied. Because the field of view is large the effect from sky curvature is non-negligible (see Section 1.7). This was set to -1 to allow the CLEAN algorithm to automatically handle the data.

### 2.3.5 Self-Calibration

Calibration on the primary and secondary calibrators assumes a model with constant amplitude and zero phase (a point source). Self-calibration then uses a model of the source to solve for antenna-based amplitude and phases as a function of time. Starting with phase-only self-calibration, a model is generated through imaging in tclean, the gain calibration solutions are calculated and applied, and then the data is re-imaged. This is continued iteratively until the phase-only self-calibration is not providing any improvements. After this an amplitude calibration can be carried out if there are any amplitude-based artifacts in the data, but this could cause a change in the flux of the sources, so it should be handled carefully.

To be able to carry out self-calibration a high signal-to-noise ratio (SNR) is needed. From the CASA guides\(^\text{30}\) the recommended minimum value is given by:

\[
\frac{\text{Peak}}{\text{RMS}} > 3\sqrt{N} - \frac{t_{\text{int}}}{\sqrt{t_{\text{solint}}}},
\]

Eq. 2-1

where $N$ is the number of antennas, $t_{\text{int}}$ is the total time on the source, and $t_{\text{solint}}$ is the solution interval used to calculate the corrections. In the calculation of the minimum value, I found the majority of the sample could undertake self-calibration with a $t_{\text{solint}}$ value of 60s. I also applied CLEANing and the self-

\(^\text{30}\) [https://casaguides.nrao.edu/index.php/Self-Calibration_Template](https://casaguides.nrao.edu/index.php/Self-Calibration_Template)
calibration process via interactive self-cleaning to manually identify nearby bright sources in order to remove contaminating effects. However, self-calibration made very little improvement to the dynamic range, RMS, and image quality, therefore the final images present in Chapter 5 have not been self-calibrated. It was also used to try and increase the detection of the fainter sources, or non-detections with bright sources in the image area, and although minor numerical differences could be seen in the dynamic range and RMS, there were no detectable differences to the images.

2.3.6 POST-IMAGING ANALYSIS

Having generated the final images, they can be either exported as fits files using exportfits or saved as a fits file using the interactive mode in viewer. This allows the image to accessed by other software such as DS9, or for use with python applications.

The main statistics calculated for the images were the maximum flux and the rms (background noise). The command, imstat, calculates all the relevant statistics on an image and each can be called. Alternatively, the interactive viewer can be used with the statistics panel open within the regions display. To obtain the rms an empty region containing no sources must be selected and the value measured. To obtain the peak, any sources in the region must be selected and the value determined. When the image contains just a few sources this method works just as well as imstat. However, with the large 33 arcminute square images imstat was quicker and more efficient. The statistics for the sample of sources can be seen in Section 5.2, Table 5-2.

Further investigation of the images includes a study of their dynamics through their compact features, integrated flux measurements and spectral analysis. The techniques and results of this scientific analysis are discussed in detail in Section 5.4.
2.4 MeerKAT

Similar to LOFAR, MeerKAT is a precursor to the SKA. The 64 13.5 m antennas will be incorporated into the SKA1-Mid towards the end of its construction phase. The array has a maximum baseline of 8 km, with 70% of its collecting area within 1 km. The array is equipped with three receivers: 544 – 1088 MHz (UHF), 856 – 1712 MHz (L-band), and 1750 – 3500 MHz (S-band) (Jonas 2009; Booth & Jonas 2012; Jarvis et al. 2016; Jonas & MeerKAT Team 2016; Renil & van Rooyen 2018; Renil 2019; Maddox et al. 2021)

With its multiple receivers, MeerKAT is able to investigate many of the science goals described in Section 1.10. There are eight large-scale survey projects which have been approved (Jonas & MeerKAT Team 2016; Maddox et al. 2021), of these there are two radio continuum surveys (Booth & Jonas 2012). In Chapter 6 I use images from the MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE) survey (Jarvis et al. 2016). This large-scale survey project, when complete, will cover 20 deg^2 over four fields (COSMOS, E-CDFS, ELAIS-S1 and XMM-LSS) to a depth of ~2μJy at 1.28 GHz with a resolution of ~6 arcsec (Jarvis et al. 2016; Maddox et al. 2021; Hale et al. 2022; Heywood et al. 2022; Whittam et al. 2022). MIGHTEE is a galaxy evolution survey studying the formation and evolution of galaxies and will be crucial for determining redshifts for the radio sources in those fields (Heywood et al. 2022). It should be noted that I did not generate any MIGHTEE mosaics or images used in Section 6.1.3. The overall process is similar to the one used by LOFAR, see Section 2.1.3, and the specific details and software used are described in detail by Heywood et al. (2022).
2.5 Summary

This Chapter has covered the different imaging datasets and catalogues used throughout my thesis and how they were generated, with an emphasis placed on the methods that I directly applied myself. I have introduced the LoTSS DR1 catalogue and the DR2 images, LOFAR Galaxy Zoo, the parent optical/IR catalogues, the VLA observations and MeerKAT datasets which are used extensively throughout this thesis. In summary:

(i) The LoTSS DR1 catalogues have been described in detail, including the source finding process, the association of components, and the optical host cross-identification techniques

(ii) I have introduced LOFAR Galaxy Zoo, which I use as a comparison and truth table for the likelihood ratio analysis in Chapter 4

(iii) The parent optical/IR catalogues for the cross-identification process have been described, as well as the improved catalogues required for the ongoing work in Chapter 6

(iv) The LoTSS DR2 image processing pipeline has been briefly described. The improvements of these images over DR1 have been discussed, justifying their use with extended radio galaxies

(v) The final survey statistics have been compared to contemporary and long-standing surveys, demonstrating that LOFAR is a competitive telescope in the SKA era

(vi) The VLA observations have been described in detail, along with the steps that I undertook to reduce and image the data

(vii) MeerKAT and the MIGHTEE survey have been introduced for the discussion in Chapter 6 on the feasibility of adapting my work to other datasets
3 RIDGELINE TRACING FOR EXTENDED RADIO SOURCES

“Just because something works doesn’t mean that it cannot be improved.”

Shuri,
Marvel’s, Black Panther


In this chapter I present a novel idea for automated host identification, and potential morphological classification, of extended radio sources: the use of spatial information in the form of ridgelines. This idea is introduced and developed in this chapter, and then applied to these automated methods in Chapter 4. The original basis of the code was created by Judith Croston, and then extended and run on a small pilot sample (~30 sources) by Joanna Piotrowska during a summer project, with the intention of using ridgelines to study morphology. This preliminary code is the core of the ridgeline drawing part of RL-XID and the core of the ridgeline drawing algorithm has not changed. My objectives were to optimise and adapt this code in order to make it functional for a variety of applications, including cross-identification and morphological studies. A second essential task was to rigorously test it using a large dataset spanning a wide range of image properties and radio source parameters for the first time.

From the late 1970’s the concept of tracing the direction of fluid flow along a jet using the radio brightness has been used, especially in the context of dynamical modelling (e.g., Blandford et al. 1978; Icke 1981; Gower et al. 1982; Condon 1984; Hunstead et al. 1984). More sophisticated ridgeline analysis and algorithmic approaches are largely associated with VLBI studies (e.g., Britzen et al. 2010; Karouzos et al. 2012; Perucho et al. 2012; Vega-García et al. 2019). Similar techniques have been used to study other types of sources, such as the X-ray binary jet SS433 (e.g., Blundell & Bowler 2004). Total intensity ridgelines
based on the method of Pushkarev et al. (2017), where the integrated intensity is equal on both sides of the ridgeline, have been used by multiple authors to investigate properties of the ridgelines themselves, such as their spectral index and the electric vector position angle (e.g., Li et al. 2018; Pushkarev et al. 2019; Kravchenko et al. 2020; Lico et al. 2020).

Using a similar approach to Pushkarev et al. (2017), I have developed a new python code (RL-Xid)31 to generate total radio emission intensity ridgelines and investigate their application towards optical host identification and morphological classification of radio sources. A ridgeline is defined as a piecewise linear pathway of connected points of highest intensity, separated by a full width of a telescope beam.

In the case of AGN jets, a ridgeline is intended to trace the direction of fluid flow. Under the assumption that jets are generated by the supermassive black holes residing at galactic centres, and that the radio emission is typically laterally symmetric about the direction of the jet flow, each ridgeline should pass through (or near to) the centre of its host galaxy (see Figure 3-1).

31 https://github.com/BonnyBlu/RL-Xid/tree/main/LQFAR/DR1
This chapter introduces RL-XID and discusses the steps I undertook to develop and extend the preliminary code in order for it to be applicable to cross-identification. Section 3.1 introduces the specific data set that I have used and how I have selected the trial set that is used to test RL-XID. The rest of the chapter is split into three main sections. Section 3.2 describes the final structure of this part of the code. In Section 3.3 I discuss the modifications applied to the code that made it possible to successfully draw ridgelines and allow it to be used for cross-identification purposes. The final performance of the code is presented in Section 3.4.
3.1 Data Selection

I selected the final sample for testing and demonstrating the code performance from the 23,344 sources defined as radio-loud AGN by Hardcastle et al. (2019) and compared against the combined optical/infrared Pan-STARRS and AllWISE catalogue used by Williams et al. (2019) (see Section 2.1.4.2). I chose to focus on AGN during the method development stages to avoid contamination from large star-forming galaxies. It should be noted, however, that initial testing indicates that while the method is motivated by jet morphologies, it also performs successfully on extended star-forming galaxies, because their emission is typically symmetric about the major axis with a centrally located peak.

In the process of preparing my data, the combined Pan-STARRS/AllWISE catalogue showed a number of sources with positional errors over 1 arcsecond in both the RA and DEC. These sources can have a significant impact on my work, as described in detail in Section 4.2.1, and therefore they were filtered out. This removed ~105,000 (~0.4%) of the sources from the catalogue and produced no obvious detrimental effect to the final results discussed in Section 4.2.5.

Source size is a necessary input parameter for my method (see Section 3.2); however, the Williams et al. (2019) catalogued sizes are only rough approximations for complex extended sources in which multiple PyBDSF components have been associated (see Section 2.1.4). Instead, I make use of the source sizes determined by Mingo et al. (2019) using the LoMorph code. The Mingo et al. (2019) sizes are calculated from an image thresholded at the higher of 4 times the RMS or 1/50 of the peak brightness by determining the greatest distance between two non-zero pixels assumed to be part of the source.

Before making use of the full Hardcastle et al. (2019) AGN sample, I selected a smaller subsample of extended sources that I could use to build up the changes to the code. Using the sources classified as AGN from Hardcastle et al. (2019) the intention was to find a set of large and bright sources which produced the most successfully drawn ridgelines with the base code. This would allow for a trial sample to be taken from the AGN population, which I could work with to improve the code, and lead to a potentially interesting set of sources for morphological studies. Having optimised the code for the trial sample it can then be applied to more complete samples.
Before selecting this trial sample, I made a couple of modifications to the code to improve both the ridgelines and the output images. The significant change to code that affected the potential ridgelines was the incorporation and adaptation of a simple masking code from Mingo et al. (2019). This piece of code masks out the external emission to prevent the ridgelines from being drawn off course, as extraneous emission can influence the average weighted direction (see Section 3.2.1). A source mask is generated to exclude the background noise, artefacts, faint uncatalogued sources, and bright nearby sources, ensuring that the ridgeline does not extend beyond the boundary of the source. The output images themselves were then cropped and centred, to zoom in on the source and ridgeline (see Figure 3-2).

To define the subsample of large and bright sources I needed to determine a suitable flux and size cut to apply to the data. To work out where to apply this cut to create my trial sample the initial masked code was run on all the sources and the successes and failures were tallied. A success is considered to be a source that outputs a completed ridgeline; a failure does not and is returned in the log file. This is shown in Figure 3-3 where the ratio of successes has been plotted for the whole flux density and size range.
Figure 3-3 – The plot shows the spread of the ratios of successes with the initial code. This is the combined result of successes for both the size and flux trial runs. The axes are given as the $\log_{10}$ values of the total flux and size. The purple vertical line shows the chosen flux cut and the blue dashed line shows the chosen size cut where the successes per binned data are highest in the top right corner, indicating the code is less successful to the left and below these lines.

This was done to allow the selection of the values for size and flux density at which the successes are constantly at a fraction of over 50% for each bin. From the graph in Figure 3-3 this occurs in the size range of $> 60$ arcsec and for fluxes $> 30$ mJy. Selecting these as the boundaries gives a working set of 991 large and bright sources, with a preliminary success rate for drawing ridgelines of 78.4% (777) sources. As discussed in Section 4.2.5 this set also works as an excellent trial sample for my later use of ridgelines for host identification, and the code is then later applied to the full sample set.
3.2 DESCRIPTION OF THE RL-\textit{Xid} CODE

In this Section I describe the final version of the RL-\textit{Xid} code, after implementing a series of adaptations and improvements, which are described in detail in Section 3.3. RL-\textit{Xid} is written in Python using standard packages as well as Sci-Kit Image\(^{32}\) (van der Walt et al. 2014), Astropy\(^{33}\) (Astropy Collaboration et al. 2013, 2018), and PyRegion\(^{34}\). Figure 3-4 shows the workflow of the code involving three main parts, each of which are described below in Section 3.2.1 (Preparing the image), Section 3.2.2 (Initial ridgeline detection), and Section 3.2.3 (Tracing the ridgeline).

RL-\textit{Xid} acts on a set of input image arrays, to which a threshold has been applied to mask extraneous emission. The threshold is set at the higher of (i) 4 times the locally measured RMS noise, or (ii) $1/50$th of the source’s peak flux density. The latter dynamic range criterion was found to provide an optimal threshold for image analysis of bright sources in this dataset by Mingo et al. (2019). There are two outputs for each input source: text files tracing the ridgeline and an image of the source with the ridgeline traced on top of it. If a source has a successfully drawn ridgeline it is defined as a Completed source, and the code generates two joint text files, each containing information on the location of the ridge points, the angular difference in radians between two consecutive points and the length of the ridgeline in pixels.

The code also generates an image of the source after the image preparation steps described in Section 3.2.1, with the ridge points overlaid and joined to form the ridgeline (See Figure 3-5). If the code fails at any point during the process the source is deemed a Failed source and the processed image is stored and a file containing a list of all the sources and type of error is produced. The key steps in the process are shown in Figure 3-4 and Figure 3-5.

\(^{32}\)https://scikit-image.org/
\(^{33}\)https://www.astropy.org/
\(^{34}\)https://pyregion.readthedocs.io/en/latest/
Figure 3-4 - The workflow of RL-XID. There are three main stages in the code: Image Preparation, Initial Ridgeline Detection and Ridgeline Tracing. The various routes by which the code can produce an error and pass the source out as a Failed are shown with the dashed lines. The different processes carried out by the code are shown in the rectangular boxes with the decision restrictions in the diamond boxes. The full sample size is given in the Image box and the number of sources passed out as each type of Failed is given, as a percentage of the full sample (black text) and as a percentage of the total number of Failed (blue text). The final number of Completed and Failed sources is given as a percentage of the full sample. A detailed description of the process is given in Section 3.2.3.
Figure 3.5 - A zoomed-in image to illustrate the different stages of the ridgeline process (see text for full description). The black cross is the initial starting point, the magenta triangles represent the search sectors, the cyan dots represent the located ridge points, the white circles represent the masked out areas around the previous points and the red arrows show how the points are joined together to form the final ridgeline.
3.2.1 PREPARING THE IMAGE

The image is first prepared to remove any non-associated sources and extraneous emission. This confines the ridgeline process to emission contained within the source of interest. The original image FITS file is trimmed down to a smaller cut-out twice the source size, centred on the flux-weighted LOFAR catalogue position. The small cut-outs remove any distant region of high emission which could influence the direction of the ridgeline. These higher emission regions can impact the dynamic range displayed for the source in the output image, making it harder to observe peaks in the source.

The component masking and FloodFill codes from LoMorph (Mingo et al. 2019) are applied to mask nearby non-associated PyBDSF components, and remove extraneous emission not related to associated components from the cut-out. The component masking and flood-fill stage enables the masking of all emission not associated with the source and is explained in full detail in Section 2.2 of Mingo et al. (2019). In summary, a mask is made that contains all pixels within the Williams et al. (2019) catalogued Gaussian components associated with the source, and excludes any nearby components catalogued as not associated; the Python skimage.measure.label routine is then used to identify connected islands of emission, which are used to extend the source's outer boundary beyond the Gaussian components to include any connected emission. In this way a source mask is generated that excludes background noise, artefacts, and faint uncatalogued sources, as well as nearby bright sources. This careful masking of un-associated emission from around the source is essential to ensure that the ridgeline traces only associated emission and does not extend beyond the boundary of the source.

Finally, the image is smoothed through a convolution using a cross shaped, centre weighted kernel. The convolution is performed to help remove any localized edge effects due to the component masking. Erosion is an skimage.morphology function which is performed, using an octagonal kernel, to emphasise the brightest regions in the image above a given threshold. The octagonal kernel represents the LOFAR beam shape, and as the Erosion function minimises the pixel values over this area (centred on the centre pixel), this highlights the brighter areas whilst enlarging the fainter ones. The Erosion and convolution kernels were carefully tested to make sure that the optimal size

35 https://scikit-image.org/docs/dev/api/skimage.measure.html#skimage.measure.label
36 https://scikit-image.org/docs/dev/api/skimage.morphology.html#skimage.morphology.erosion
and weight were used to balance the amount of image eroded and noise remaining. A kernel size of just below beam width was found as optimal (see Figure 3-6 and Section 3.3.1).

![Figure 3-6](image_url)

Figure 3-6 – Two images demonstrating the before and after of the erosion process. On the left is an image of the source, and on the right is the same source passed through the erosion and convolution functions. The right image clearly shows the maximum found and trimmed edges from erosion.

### 3.2.2 Initial Ridgeline Detection

As the ridgeline is intended to trace the pathway of highest flux density in the radio source, the maximum brightness inside the source region is taken as the initial point. This maximum is calculated as the pixel inside the source region with the highest value. This guarantees that the ridgeline passes through the brightest point of the source, which in many cases will coincide with an AGN core or hot spot region, which I would also expect to lie along the ridgeline and so acts as a satisfactory starting point.

The initial directions, in which RL-Xid searches for the ridgeline steps, are determined by finding the first two local maxima closest to the initial point. If there is only a single maximum found, then the complementary direction at $\pm \pi$ radians is taken (see Figure 3-5). If no direction can be determined, the initial point is masked, and a new maximum is located by taking the pixel with the next highest value within the source regions. The erosion and direction-finding processes are iterated until starting directions are found or a maximum number.
of iterations is achieved (see Figure 3-4). The initial directions form the centres of two initial search sectors. As given in Table 3-1 the step size of the code, $R$, is set to 5 pixels. This is roughly the same size as a beam’s width, with 1 pixel $\sim$1.5 arcsec and an angular resolution of 6 arcsec. Further optimisation of $R$ may improve the performance of the code in particular situations. After exhaustive testing, a half sector size was set as $d\Phi = 60$ degrees. This produces optimal results between ridgelines that are too straight to be representative and those that, in some situations, tended to turn back towards the centre rather than continuing along the extent of the source.

Table 3-1 – A list of the adjustable parameters in the code. The name of the parameter is listed along with the current value used with LoTSS DR1, and a description of how it is used. These parameters are likely to require adjusting according to survey specifications.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE (units)</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>5 (pixels)</td>
<td>Starting step size between each ridge point. Set to LOFAR beam size in pixels.</td>
</tr>
<tr>
<td>$d\Phi$</td>
<td>60 degrees</td>
<td>Half size of the search sector.</td>
</tr>
<tr>
<td>rdel/ddel</td>
<td>$\pm 0.000416667$</td>
<td>The degree to pixel conversion factor, currently set to the LoTSS configuration.</td>
</tr>
<tr>
<td>rad</td>
<td>2.5 (pixels)</td>
<td>Radius of the mask over an unsuccessful initial point determination. Set to the resolution of the LoTSS beam.</td>
</tr>
<tr>
<td>ipit</td>
<td>6</td>
<td>The number of iterations of reattempts on the initial point function.</td>
</tr>
<tr>
<td>Rmax</td>
<td>$0.95 \times$ source size</td>
<td>The total length permitted for each half of the ridgeline.</td>
</tr>
<tr>
<td>Jlim</td>
<td>$0.4 \times$ source size</td>
<td>The limit on the ridgeline length at which it is permitted for the algorithm to perform a 'jump'.</td>
</tr>
<tr>
<td>Jmax</td>
<td>source size</td>
<td>The maximum distance to which a ridgeline can search when performing a 'jump'.</td>
</tr>
</tbody>
</table>
3.2.3 TRACING THE RIDGELINE

Having masked all but the initial search sectors, an annular slice of the sector is searched for a maximum brightness value. This slice is created by masking the previous point and any points greater than \( R \), typically leaving only a segment of pixels (see Figure 3-5). If the search area is empty, the search is repeated, increasing the width of the segment by increasing \( R \) one pixel at a time. This continues until either a value is found, or \( R \) has increased to be greater than \( R_{\text{max}} \); see Table 3-1. The \( R_{\text{max}} \) parameter, which sets the overall ridgeline maximum length, is set to a value related to the input catalogued source size, obtained as described in Section 2.1.

I was able to relate \( R_{\text{max}} \) to the source size as I would expect for typical morphologies, allowing for source bends, the overall ridgeline length to be unlikely to exceed the total source extent by more than a factor of \(~2\). As the two ridgeline halves are generated separately, and in some cases the starting point is not the source centre, there is a trade-off between the edge cases of (i) highly asymmetric sources that should not be restricted from completing their path and (ii) complex, more amorphous objects where too large a value of \( R_{\text{max}} \) will lead to a ridgeline that continues to explore regions of lower dynamic range after it reaches close to the source edge, leading to 'looping' (see Section 3.4.1.1). My strategy of increasing \( R \) where emission is not found within the search region allows the ridgeline to jump any nearby gaps in emission, for example in an FRII morphology where an emission-free region between the two lobes may be present; this is demonstrated in a later section (see Figure 3-7-d).

Once a maximum point has been determined it becomes the starting point for the next step. The previously identified point is recorded and masked out in a circle of radius \( R \). This prevents any future searches in the area from selecting the previous points or nearby points within a beam area. A search sector is created on the newly identified starting point, with a direction centred using the brightness-weighted average of the previous annular search slice (see Figure 3-5).

From here the point determination is repeated. Again, if the search area is empty, \( R \) is increased until a new point can be found (i.e., the ridgeline is permitted to 'jump' empty regions), or restrictions are met. Here the length is restricted again to \( R_{\text{max}} \); however, the jump is only permitted if the ridgeline is under \( J_{\text{lim}} \) and must not exceed \( J_{\text{max}} \) in total, see Table 3-1 for definitions and
values. This helps prevent the ridgeline from extending to any possible remaining external un-associated emission.

Similarly to $R_{\text{max}}$, the values of $J_{\text{max}}$ and $J_{\text{lim}}$ were determined through a series of tests and visual checks for quality, and will need to be adjusted for different surveys. These values optimized the successful outcomes and the quality of the ridgelines by reducing issues such as extending to nearby sources and maximizing the number of FRII jumps achieved.

After the first point in each direction has been determined, the process iterates until ridge points can no longer be located. The ridgeline is completed when the restrictions are met, or when no viable points are found within the search sector, as shown in Figure 3-4. The final step outputs the information about the ridgeline's individual points as a text file. This includes the location of the ridge points in pixels, the angular direction of the ridge points in radians, and the length of the ridgeline. An image of the source with an overlay of the ridge points plotted and connected (see Figure 3-5), is saved for visual comparison.

Using Figure 3-5 the complete ridgeline definition process can be summarised as:

(i) Initial point is found (black cross)
(ii) Initial direction and search sectors are located - If not, source flagged as a Failed
(iii) Initial points are determined - If not, flagged as a Failed
(iv) Search sectors are placed at the first ridge points in the direction from the initial point (magenta triangles are examples of how the sectors appear)
(v) New ridge points are determined (cyan dots) - If the search area is empty the step size can increase to allow for bridging of gaps in emission
(vi) Previous points are masked around, with a radius one step size (white circles)
(vii) The most recent ridge points are used for search sectors
(viii) Repeat steps (iv) to (vii) until the end of the source is reached, or the ridgeline is greater than $R_{\text{max}}$
(ix) Ridgelines are completed for both directions.
(x) The information about the ridgeline is printed to a text file and an image of the source is produced with the ridge points (cyan dots) joined together (red arrows), leading out from the initial point (black cross) overlaid on it.
Throughout the ridgeline creation process there are steps where the code can fail and output a Failed source (see Figure 3-4). During the FloodFill process, cataloguing errors and mismatching component information can cause the sources to fail. There is a chance a source may fail the Erosion process, mainly due to catalogue errors creating empty source images. The Failed source is designated as having an ID Out of Region when these catalogue errors produce incorrect cut-outs; the initial point is deemed to be outside the initial search area.

Assuming no cataloguing errors occur, if the initial point iterations exceed the ipit parameter (see Table 3-1 for definition and value) without finding initial directions then the source has failed due to lack of suitable initial points. Likewise, when searching for the first points, if a value is not found within Rmax the source is classed as a Failed. This may occur where the initial point is on one lobe and the diagonal distance to the other lobe is greater than Rmax, or where the initial point is on the edge of the source and there is no first point to be found in one direction. Both ‘first’ points must be found for a source to continue to Completion.

If the code successfully runs through points (i) to (x) listed above, then the source is classified as Completed and the output files are ready to be used for the ridgeline process in Chapter 4. If any errors prevent this from happening, then the source is classified as a Failure. The final code performance is discussed in Section 3.4.
3.3 Code Adaptation

This section discusses the modifications made to the ridgeline drawing part of RL-XID as a result of the testing and development briefly introduced in Section 3.2. The changes I describe were made to the base code to produce the final ridgeline algorithm described in Section 3.2. I carried out the initial development of the method, using a dataset containing 991 of the largest and brightest sources, with total flux density > 30 mJy and a size > 60 arcsec. The details on how this sample is determined are given in Section 3.1. Prior to the changes described here, the success rate of the base code was 78.4% and Section 3.3.1 concerns the improvements made to this code whilst it uses the host galaxy as a starting point. Section 3.3.2 focuses on the how the code was adapted further to remove the host galaxy as an initial point. The aim here was to generate ridgelines which could then be applied to cross-identification of sources where the host galaxy was unknown.

3.3.1 Preparing a Set with Hosts

The initial aim was to improve the performance of the base code on the trial set. There were a few key areas that could be investigated in order to reduce the initial number of failing sources. The most common reason the code outputted a failed source was because it was unable to find two initial directions to begin drawing in. Another reason for the initial ridgelines from the base code to be of poorer quality was because the algorithm was not programmed to ‘jump’ over any gaps in emission unless they were at the start of the ridgelines. This meant that core bright FRIIs had ridgelines that were not fully complete. As well as these, any remaining extraneous emission might take the ridgelines off course.

The initial version of the code was written to start from the known host galaxy. One of the main reasons for failed sources in the beginning was an inability to find two initial directions to start from. I discovered that most of these occurred on centre bright sources and so, to counter this, a small circular mask was placed over the location of the host and the finding of the initial directions was run again. This proved to be successful in removing several of the centre bright failing sources.
I looked at tackling the problem of extraneous emission and traversing gaps simultaneously, as solving both these problems can affect each other. As I looked at improving the masking of extraneous emission this had an effect on the size of the gaps. However, if there is extra emission around, a routine to traverse gaps may travel to unwanted regions in the image.

During the ridgeline process the image is eroded (see Section 3.2.1) which helps to remove any remaining noise features and highlight areas over a certain brightness threshold. These highlighted maxima are used to determine the initial directions the code should take. The shape of the erosion kernel is set to Octagon(3, 3) in the base code. This is slightly larger than the LOFAR beam size. Setting this kernel to have a shape of Octagon(3, 2) produces a kernel which is slightly smaller than the beam size. The smaller kernel would mean less of the image is eroded, leaving more for the ridgeline calculations to work with, however there will be more noise present surrounding the source and a possibility of highlighting features within a beams size.

Gaps in emission are common in extended sources, particularly with FRIIs, which may have a structure of two lobes at a separated distance from a bright central core. The base code was designed to jump gaps in emission if they occurred during the process of finding the initial point of the ridgelines. This allowed for the host to be offset from the source or centred in an emission gap.

Where a source has the structure of a bright core and two separated lobes, the base code could often find initial points in the core and then be unable to bridge the gaps in the emission. I applied a similar piece of code from the initial point function to the ridge point function to allow the proceeding steps to jump over emission gaps.

Conditions were set which prevent the ridgelines from jumping once already drawn sections reached a certain length. This prevents the ridgeline from jumping to any erroneous external emission. Applying a maximum length to how far the ridgeline is allowed to jump up to prevents extension beyond the dimensions of the source.

Various combinations of jumping parameters and erosion kernels were tested, and the outcomes visually compared to find those producing optimal ridgelines; a combination of being able to bridge emission gaps without moving into erroneous external emission, and those where the erosion provides a good ridgeline without introducing excess noise or reducing the source.
In the end the code was set with an erosion kernel of Octagon(3, 3) to reduce noise. The parameters for bridging gaps were set to allow searching for further possible regions of emission if the current length of one side of the ridge is less than $0.25 \times \text{source size}$, and the jump cannot extend to longer than one third of the maximum length of the ridgeline, which is currently set to $0.75 \times \text{source size}$. Out of the set of 991 sources there were 91% (902) successfully drawn ridgelines.

Finally, to further reduce the possible effects of external emission on ridgelines, the possibility of jumping to extraneous emission and to speed up the process, the larger cut-outs were cutdown. They are centred on the LOFAR catalogue position and extend in a square shape to $2 \times \text{source size}$. The cut-outs reduced the number of successfully drawn ridgelines to 89.5% (887). The runtime was reduced by 60% and a visual inspection demonstrated a better-quality sample with fewer sources displaying features such as extending to external emission or looping back towards the host.

These improvements to the code increased the success rate from 78.4% with the base code to 89.5%, for the version of the code written to use the host position as its starting point.

### 3.3.2 Changes Made by Removing the Hosts

The pilot version of the code available at the start of this work used the optical host location to initialise the ridgeline. While this is useful for drawing high quality ridgelines, I wanted to develop a method that could be used for sources that don’t have optical IDs. This section discusses the adaptations made to the code to remove the optical host as the starting point. This is a crucial step if the ridgelines are to be successfully used as part of the algorithm of the cross-identification process. The main challenges here were deciding and testing an appropriate location for the initial point to be, and then re-evaluating the parameters in place beforehand for ridgeline length, and ‘jump’ permissions.

The most obvious initial starting point based only on radio catalogue information is the catalogued LOFAR radio centroid and so I adapted the code to use this as a starting point. This was chosen because for many sources, particularly if they were simple single component, the catalogue position often lies close to the host.
galaxy. For this reason, the ridgelines generated in this way worked well and were not dissimilar from those described in the previous section.

Both for ridgelines starting from the host galaxy and those starting from the LOFAR catalogue position one common feature was a sharp deviation from a smooth path near the starting point. These peaks form when the initial point is offset from the true underlying ridgeline. To counter this the initial point was taken to be the maximum from the erosion process that was closest to the LOFAR catalogue position. This reduced the number of ridgelines with a triangular structure around their starting point. However, the use of a maximum from the erosion process runs the risk of causing an error where the initial directions are not found. The algorithm requires two nearby erosion maxima to work, and any selected maximum near the edge of the source will reduce the possibility of two nearby selectable points.

The final initial point method I implemented was to mask all but the component ellipses for the source and then select the maximum flux value in this region. It is expected a ridgeline based on following the path of maximum flux intensity would have the maximum flux point on it. It also removed the reliance on a catalogue position. It does still maintain the risk of the initial directions failing due to being unable to locate two maxima, as one may coincide with the starting location. This reduced the number of failed sources and produced better quality ridgelines.

Having obtained an initial point independent from the host galaxy, I could revisit the parameters for jumping emission gaps. This needed to be re-explored because the maximum flux value may not be central in a source. The ridgeline may require the ability to travel further, bridge larger gaps, and do this earlier or later than in previous versions of the code. I wanted to allow as much flexibility as possible with where the ridgeline can travel without having to worry about extension into external emission, so I adapted and applied the FloodFill code from Mingo et al. (2019) (see Section 3.2.1). Combined with the masking, this removes any extra emission not associated with the main source. This process is done within a small distance of the main source and combined with the masking, for most sources, all external emission is removed. A small number still have non-associated sources close by and some emission remains present. The application of the FloodFill code meant I could revisit the ridgeline length and jumping parameters. Several variations were tested and visually inspected. The final code allows each half of the ridgeline to have a
maximum length of $0.95 \times \text{source size}$, jumps can be performed under $0.4 \times \text{source size}$ and can be as long as the maximum length of the ridgeline, as shown in Table 3-1.

Most of the failures at this stage were due to a lack of initial directions being found. The majority of these were an inability of the code to find two maxima from the erosion process. By iterating the initial point and initial direction functions around the maximum flux points the number of failures was reduced. The total number of iterations the code runs through is 6, this best optimises the number of successfully drawn ridgelines for the total amount of run time. The final success rate is 95.9% (950) with a runtime of 18.5 hours. A comparison of the successful outcomes and runtimes for each version of the code can be seen in Table 3-2. As can be seen in Table 3-2 the combination of these final adjustments has taken the ridgeline drawing success rate up from 89.5% with hosts to 95.9% without hosts.

<table>
<thead>
<tr>
<th>SUCCESS RATE</th>
<th>RUNTIME (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASIC CODE</td>
<td>78.4% (777)</td>
</tr>
<tr>
<td>WITH HOSTS (+ adjustments)</td>
<td>89.5% (887)</td>
</tr>
<tr>
<td>WITHOUT HOSTS (+ adjustments)</td>
<td>95.9% (950)</td>
</tr>
</tbody>
</table>

Table 3-2 - The success rates of the different stages during the improvements of RL-XID. The table shows the percentage (and number) of successfully drawn ridgelines in the set and the amount of time it takes the code to run each iteration.

Having applied these changes to the base code, RL-XID was ready to be adapted further for use with optical host cross-identification.
3.4 Results

This ridgeline drawing process has two possible outcomes: Completed, where a ridgeline has been drawn, or Failed. For 95.9% of the sample the outcome was Completed (see Table 3-3 in Section 3.4.1.1). This generates output files containing the numerical and graphical information. Examples of Completed sources can be seen in Figure 3-7, where a variety of ridgelines are shown demonstrating how they can pick out simple, straight structures in Figure 3-7-a, to more complex, angled sources in Figure 3-7-b. This complexity can lead to distinguishing different morphologies such as wide angled tail (Figure 3-7-c) and narrow angled tail sources. The Completed dataset is described in detail in Section 3.4.1.1 and the Failed outcomes discussed in more detail in Section 3.4.1.2.

3.4.1.1 Completed

A Completed source is one where the code managed to complete and draw a ridgeline in two directions from the initial point. A visual inspection of the Completed sources was carried out to check the quality of the ridgelines. Low quality ridgelines fall into two categories: those which are caused by rare cataloguing errors and those where the code has produced a ridgeline containing analytical issues, as discussed below. These have produced ridgelines which are faulty or misleading in some aspect. They may not necessarily be unusable depending on the application of the ridgelines.
Figure 3-7 - Four examples of successfully drawn ridgelines (1 pixel ≈ 1.5 arcsec). (a): A simple straight source with a ridgeline. (b): A more complex, curved source demonstrating the ridgeline’s ability to follow the path of the radio galaxy. (c): A wide angled tail radio galaxy with the morphology clearly traced by the ridgeline. (d): An example where the ridgeline has successfully jumped from one part of the emission to another in an FRII.
Figure 3-8- An example of a low-quality ridgeline produced from a Masking or Flood Fill error (1 pixel ≈ 1.5 arcsec). A large portion of the source has been masked either through an overlapping source or a mis-identified region, causing a completed but inaccurate attempt at a ridgeline.

The catalogue errors occur with the Erosion and FloodFill functions. Overlapping, un-associated sources or mis-identified components in the catalogue can lead to large parts of the source being masked out (see Figure 3-8).
The code will have attempted to draw a ridgeline for these sources given the emission present with varying degrees of success. These cataloguing errors are evident in 1.5% of the sample; 1.1% in the *Completed* sources (see Table 3-3) and 0.4% in the *Failed*. Examples of the analytical issues are shown in Figure 3-9 and described below, stating their percentage occurrence within the successfully drawn ridgelines:

- **Extended (2.1%) (Figure 3-9-a)** – The ridgeline has jumped or extended out of the apparent source into nearby, un-associated emission. This is due to incomplete masking or flood filling, or catalogue errors.

- **Looping (5.5%) (Figure 3-9-b and Figure 3-9-c)** – The ridgeline has managed to create a full loop in its pathway or has looped back at the ends. Full loops are more often found in large sources where the masking around the previous points fails to prevent a circular pattern from occurring. For a source to be classed as having a loop back the ridgeline has to take three or more steps returning towards the centre, without indication in the image of an associated tail or back flow in the location of these ridge points.

- **FRII Jump Failed (1.1%) (Figure 3-9-d)** – The ridgeline on some FRII sources did not make the jump over the central emission gap, or over a gap from the central core to one of the outer hot spots.

- **Both Same Direction (0.8%) (Figure 3-9-e)** – Both ridgelines have travelled in the same direction from the initial point. With sources that have very smooth emission around the initial point this can lead to both ridgelines heading in the same direction.

- **Not Representative (1.9%) (Figure 3-9-f and Figure 3-9-g)** – The ridgeline does not represent the believed pathway of the jet. In these instances, the correct path has not been determined and the ridgeline has often travelled transverse to the source as in Figure 3-9-g or has been unable to correctly distinguish the separation between tails, Figure 3-9-f.

- **Too Short (1.8%) (Figure 3-9-h and Figure 3-9-i)** – The ridgeline is too short for the source. This may occur after an FRII jump and might be because of the length restriction in place in the code (see earlier discussion in Section 3.2.3).
Figure 3-9 - Examples of the analytical issues creating low quality ridgelines in the successful sample (1 pixel = 1.5 arcsec). These are explained in detail in Section 3.4.1.1. (a): An example of an extended issue where the ridgeline has extended to nearby un-associated emission. (b): A ridgeline containing a full loop. (c): An example where the end of the ridgeline has turned back on itself for at least three steps. (d): This ridgeline is an example where the FRII gap has not been bridged. (e): Due to the even emission of this source both halves of the ridgeline have travelled in the same direction. (f): On inspection this source would appear to be a narrow angle tail source, the ridgeline drawn does not represent this. (g): The ridgeline does not represent the source and is instead transverse to the expected direction. (h): The ridgeline has stopped short of the end of the source. (i): The ridgeline has bridged the gap in the emission; however, it is not long enough to reach the end of the source.
The breakdown of how many catalogue errors and analytical issues are present in the sample is given in Table 3-3 along with the percentages in terms of the sample as a whole and of the Completed sources. From Table 3-3 the catalogue errors account for ~1% and Analytical for ~13% of the Completed outcomes. It is intended in future releases of the code to further reduce the effects of these errors.

Table 3-3 - Results from the ridgeline drawing stage of RL-Xio on the sample of 991 sources. It gives the percentage of Completed from 950 sources, and percentage of Failed from 41 sources along with the catalogue errors and analytical issues as a ratio of the whole 991 sample and of each group.

<table>
<thead>
<tr>
<th></th>
<th>% OF SAMPLE</th>
<th>% OF COMPLETED</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COMPLETED</strong></td>
<td>95.9</td>
<td>-</td>
</tr>
<tr>
<td>Masking</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Extended</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Looping</td>
<td>5.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Fail to FRII</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Same Direction</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Not Representative</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Too Short</td>
<td>1.7</td>
<td>1.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>% OF FAILED</th>
<th>% OF FAILED</th>
</tr>
</thead>
<tbody>
<tr>
<td>FloodFill</td>
<td>1.1</td>
<td>27</td>
</tr>
<tr>
<td>Erosion</td>
<td>1.5</td>
<td>37</td>
</tr>
<tr>
<td>Initial ID Out Of Region</td>
<td>0.9</td>
<td>22</td>
</tr>
<tr>
<td>Unable to Find Initial Directions</td>
<td>0.5</td>
<td>12</td>
</tr>
<tr>
<td>Unable to Find First Ridge Point</td>
<td>0.1</td>
<td>2</td>
</tr>
</tbody>
</table>
As the initial point is the point of maximum flux density it is expected this will usually coincide with the AGN core or hot spot region, and for the purposes of cross-identification may be situated near to the possible optical counterpart. Regardless of the analytical issues the initial point is still present on the ridgeline, and this allows for cross-identification to take place in many cases. All these analytical issues are morphological in nature, therefore up to ~13% of the Completed sources could produce morphologically misleading ridgelines. The Completed ridgeline output files contain further information regarding the location of the ridge point on the array, the length of the ridgeline, and the angular change in the ridgeline.

3.4.1.2 Fails

There are five possible ways for the code to produce an error; this produced 4.1% (41) instances of Failed sources. Two instances, Erosion and FloodFill fail through an inability to complete their functions and are the cause of 63% of the Failed. The remaining Failed are due to the ridgeline not meeting the requirements to be drawn, for example the ID Out of Region error discussed at the end of Section 3.2.3. The remaining two possibilities are simply where the source is unsuitable for the ridgeline process. Either after multiple attempts the initial conditions are not satisfied (Unable to Find Initial Directions) or from the initial point the first steps of the process are unable to begin (Unable to Find First Ridge Point) (see Figure 3-4).

As the RL-XID algorithm lays search sectors for two ridgelines in opposite directions from the initial point, it is possible certain morphologies might not be detected, such as narrow angle tail (NAT) sources. Head-tail sources are narrow angle tail radio galaxies, viewed edge on, which show sharp bends very close to the core, making it hard to distinguish both tails (Simon 1978). The cores of these radio galaxies lie close to one edge of the source and may be prone to causing the code to fail due to its inability to find a first ridge point in both directions. In order to check the effect of this, the sample was visually reviewed for head-tail sources and ~2% (22) of the sample were found to be likely head-tail candidates. Of these the Failed were visually inspected for these cases and ~27% (6) possible candidates were found, ~9% (2) were classed as Erosion errors. The remaining ~18% (4) are possible candidates for failure as head-tail sources with an outputted error of Unable to Find the First Ridge Point.
3.5 SUMMARY

In this chapter I introduced idea of ridgelines, the tracing of fluid flow along the direction of the jet. I described the origins of the base code and sample selection process, leading to the trial sample of 991 large and bright sources. I have given a detailed explanation of the process of the ridgeline drawing aspect of RL-Xid, going through the three main sections of Image Preparation, Initial Ridge Detection, and Ridgeline Tracing. There is also an in-depth discussion on the results and outputs of this initial stage of RL-Xid. This includes a quality inspection, and the implications of analytical issues on morphological investigation using ridgelines. RL-Xid is publicly available at https://github.com/BonnyBlu/RL-Xid.

I have followed this with a description of how I tested and modified the base code in order to improve its performance for use with morphological classification and host identification. In summary, the final modifications I made were:

(i) Removed the host galaxy as the initial point and using the highest flux value instead
(ii) Masked the initial point, and iterating its location to find two initial directions
(iii) Tested the Erosion parameters to optimise the amount of emission present in the source
(iv) Generated an algorithm to 'jump' gaps in emission, and tested and applied the parameters to produce the best quality ridgelines
(v) Cropped the image size and FloodFill to reduce runtime, and effects from nearby bright sources

All of these changes have together increased the ridgeline drawing success rate from 78.4% to 95.9% for the trial set of 991 sources.
4 Investigating the Application of RL-Xid to Extended Radio Galaxies

"I’m with you till the end of the line, pal."

James Buchanan ‘Bucky’ Barnes, Marvel’s, Captain America: The First Avenger


Having established that RL-Xid is able to successfully draw ridgelines on the majority of sources in the trial dataset, the next aim is to apply this technique to the larger problem of optical host cross-identification, and assess its potential for other automated processes, such as morphological classification. As described in Section 1.11, with recent and upcoming radio surveys producing vast catalogues of sources, the need for automated methods for cross-identification and classification is becoming increasingly important.

Section 4.1 introduces surface brightness profiles. These are numerical and graphical representations of the brightness along the generated ridgelines. The surface brightness profiles are used to examine the source structure, and to adapt existing methods for source host identification. The classification of the surface brightness profiles and how they might relate to FR morphologies (see Section 1.4) is discussed in Section 4.1.1. This technique is then compared to LoMorph’s (Mingo et al. 2019) FRI and FRII automated classification, and the results are discussed in Section 4.1.2.

In Section 4.2 the application of RL-Xid to find optical host galaxies is investigated. Using a method similar to that of Williams et al. (2019) I explore how ridgelines can be incorporated into the process. In Sections 4.2.1 to 4.2.4 the trial dataset is used to build and test an effective technique to statistically determine the most likely optical counterpart to a radio source: a likelihood ratio
(see Section 1.11.1). This technique is compared to LOFAR Galaxy Zoo (see Section 2.1.4.4) and tested on the full AGN catalogue from Hardcastle et al. (2019). The results are given in Section 4.2.5.
Morphological classification of extended radio sources is another process which has recently been automated, for example by LoMorph (Mingo et al. 2019), and it plays an important role in the understanding of feedback processes. Traditionally, radio-loud AGN are divided into two Fanaroff and Riley (FR) morphologies: FRI and FRII (see Section 1.4). These are defined based on the ratio of the distance between the region of highest brightness and the core on each side, and the full length of the corresponding side. If the ratio $< 0.5$, where the peak of the brightness is near the core, the source is an FRI and if the brightest peak is near the edge of the lobes, giving a ratio $> 0.5$, it is an FRII (Fanaroff and Riley 1974). Surface brightness profiles along ridgelines therefore have the potential to be used as a means to classify extended radio sources.

In addition to recording the positional information, RL-XID also records a surface brightness profile along the ridgeline, which may be used as part of the optical identification process and for morphological classification. The surface brightness (SB) profile is the measurement of SB of the radio source at each point along the ridgeline. A brightness-weighted average of nearby pixels is plotted for a graphical representation of the profile of the ridgeline. The SB profile shows the dips and peaks in brightness along the ridgeline. Using the definition of FR classification (see Section 1.4) it is expected that sources with FRI type morphology will have SB peaks near the centre of their ridgelines. In contrast, an FRII type structure should have two distinct peaks towards the ends of the ridgeline. Figure 4-1 demonstrates the distinct brightness distributions expected for FRI and FRII sources.

37 [https://github.com/bmingo/LoMorph](https://github.com/bmingo/LoMorph)
Figure 4-1 - Two surface brightness profiles with the corresponding ridgeline in the top insert. (a): The surface brightness profile for a wide-angle tail (FRI). (b): The surface brightness profile for an FRII. The profiles show the surface brightness for the distance along the ridgeline from one end, calculated as the weighted average of the surrounding four pixels. For the top image, the starting position on the SB profile corresponds to the upper leftmost end of the ridgeline, and in the bottom image the starting position corresponds to the upper rightmost end of the ridgeline.
4.1.1 CATEGORISATION OF THE SURFACE BRIGHTNESS PROFILES

In order to look at the SB profiles in more detail and use them for host identification and morphological classification, the profiles were classified according to the location of any dips or peaks. The SB profiles were split into four different groups depending upon the location of a minimum value along the ridgeline: Dips, Peaks, Both and Neither. I considered the optimally sized central region within which a peak or dip is expected to fall and found that the central 30% of the source gave the best results. This method differs from the original Fanaroff-Riley classification (Fanaroff and Riley, 1974) where they excluded any compact component situated on the central galaxy and calculated their ratio from this central location.

If only a minimum value occurs within the middle 30% of the length of the ridgeline, then the SB profile is classed as a Dip. In order to determine if a minimum value is contained in the middle 30% the lowest three values of the SB profile are taken. As the dips are meant to be global minima, which are also not the minima associated with the ends of the ridgeline, we start with the lowest; the first step is to check to see if it lies at the end of the ridgeline. This is expected, as the ridgeline will commence or terminate at the edge of the source, possibly in an empty part of the array. If the lowest point is at the end of the ridgeline the next lowest point is chosen and checked. The three points are checked in ascending order until one point not at the end of the ridgeline is found. The location of this point along the ridgeline is compared with the middle 30% of the ridgeline. If it lies in this region the source is classed as having a dip (see Table 4-1).

The ridge point with the highest associated SB is labelled the peak and its location is checked against the middle 30% of the ridgeline. If only the maximum value and not the minimum value is in this region the profile is designated a Peak. For those profiles where both a dip and a peak are found in the central region they are classed as Both, and if neither are found they are classed as Neither (see Table 4-1).
Table 4-1 – Summaries of the classifications of the surface brightness profiles. Dips, Peaks, Both, and Neither depend on the location of the maximum and minimum values. A tick mark indicates if they are located within the central 30%.

<table>
<thead>
<tr>
<th></th>
<th>MINIMUM</th>
<th>MAXIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIP</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>PEAK</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>BOTH</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>NEITHER</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1.2 **Comparison with LoMorph**

As the data are a subset of the sample from Mingo et al. (2019) this method of sub-dividing the SB profiles could be compared to LoMorph’s classification of these radio sources to investigate the potential of ridgelines for morphological identification. It should be noted the LoMorph’s classification excludes any compact component situated on the central galaxy. The LoMorph classification of the sample sources as Star-Forming, Double-double, Fuzzy blobs, Core-bright and Bad were left out, leaving a clean sample (88% of the SB profiles) of FRI (including wide angle tail (WAT) and narrow angle tail (NAT)), FRII, and Hybrids. This was done as a starting point to assess the capabilities of RL-XID to perform simple morphological classifications. The final sample from Mingo et al. (2019) consists of 2106 sources of which ~60% are FRI, ~20% FRII and ~20% are Hybrid. In comparison the final SB groups show similar percentages across the Dip and Peak groups (see Table 4-2).

Figure 4-2 shows a high number of FRI sources having SB profiles in the Peak group and the majority of the Dip SB profiles as matching sources with FRII classification. As WATs and NATs are subsets of FRIs (Owen & Rudnick 1976; Rudnick & Owen 1976; O’Dea and Owen 1985; Hardcastle & Croston 2020), it is expected that they make up a high number of the Peak SB profiles. Likewise, as FRIIs and hybrids are thought to have similar morphologies (Harwood et al. 2020) the Dip SB profiles will contain a high number of these classifications. Since Hybrids are a heterogeneous population (Mingo et al. 2019), unsurprisingly they do not fit neatly into any of the categories. This is the most likely cause of the high number of Hybrids in the Both SB profile group where
both a peak and a dip were found in the central region. Likewise, some FRIIs have a structure with a bright central core and emission gaps between lobes; this will increase the number of FRII classified sources likely to appear in the Both SB profile group. Interestingly, the Neither SB profile group has a higher FRII content. This group appears to be made up of sources with a fairly uniform surface brightness, so unambiguous classification by any method is challenging. Table 4-2 and Figure 4-2 demonstrate a link between the presence of a dip or peak in the middle 30% of a ridgeline and the morphology of a source.

Table 4-2 - The percentage of Surface Brightness Profiles which are classified as either an FRI, FRII or Hybrid, in each of the Dip and Peak groups.

<table>
<thead>
<tr>
<th></th>
<th>% DIPS (220)</th>
<th>% PEAKS (369)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRI</td>
<td>16</td>
<td>71</td>
</tr>
<tr>
<td>FRII</td>
<td>59</td>
<td>11</td>
</tr>
<tr>
<td>HYBRIDS</td>
<td>25</td>
<td>18</td>
</tr>
</tbody>
</table>

Figure 4-2 - The four surface brightness groups separated into By-Eye Classifications. This shows the percentage of the group which falls into each classification.
In addition to using the SB information for morphological classification, I also wanted to explore its use in host identification. For this purpose, I identified a location that characterised the most likely host location given the surface brightness profile. Taking the Dip SB profiles, which can be considered to have an FRII like morphology with two outer peaks, the ridge point corresponding to the location of the dip was recorded. All other sources recorded the ridge point at which the maximum occurred. For the Peak SB profiles, this was because of their FRI like morphology coinciding with a central peak; for the Both SB profiles this included those with FRI like tendencies and those FRIIs with bright central cores. For the Neither SB profiles, the peak was taken as a starting point to work with. In each group the distance between the host galaxy for this source and the corresponding dip or peak is considered to be the SB separation used in later calculations.

In conclusion, I have shown that RL-XID is extracting useful morphological information. Future work is planned to develop this capability of the code further to enable more sophisticated classifications.
4.2 Optical Host Cross-Identification

Identification of possible host candidates, when cross comparing catalogues with a range of resolutions, has often been carried out using the Nearest Neighbour technique (Kimball and Ivezić 2008) (see Section 1.11.1). Although successful for some earlier surveys, this is not practical for cross-identification over multiple wavelengths as this method can produce multiple possible matches to extended sources where the nearest neighbour ID can be wrong (Kondapally et al. 2021). The likelihood ratio method (Richter 1975) helps by statistically determining when to accept a possible counterpart depending on the properties of the radio source and the potential optical/IR host. With larger catalogues being produced by new and upcoming surveys, the increased volume of data will lead to a higher number of extended sources (or potentially multi-component sources) being observed, and multiple matches to be interpreted. Increased sensitivity will recover more extended emission, for resolutions and configurations suited for extended emission detection (see Chapters 1 and 2).

Automated methods are needed to deal with the great volume of data and to improve the characterisation of extended sources. Methods of cross-identification include variations on the likelihood ratio method (e.g., Richter 1975); this class of methods uses statistical determination of the likelihood of an optical/IR source being a matching counterpart to a radio source, based on parameters including separation, colour and magnitude of the sources, along with their associated errors. There also exist techniques using Poisson Probability (Downes et al. 1985), and Bayesian methods of hypothesis testing (Fan et al. 2015) for component matching of radio sources with realistic morphology. The success of the likelihood ratio method can be limited by sources which are too large and complex (see Pineau et al. 2016). In some circumstances the source finder is unable to correctly group separate components of large sources, or incorrectly groups multiple sources together, and the likelihood ratio is unable to correct for this (Williams et al. 2019). In these instances when automated methods cannot be used, other visual classifications have been developed, such as Radio Galaxy Zoo (Banfield et al. 2015), where citizen science is used to identify host galaxies. This can be time consuming, as multiple classifications are needed per radio source.
In the following, I make use of surface brightness information via ridgelines to improve the automated likelihood ratio method for host identification and reduce the number of sources going to human classification such as Radio Galaxy Zoo. In this way I both speed up the identification of an optical/IR counterpart and lower the chances of human error associated with visual inspection.

4.2.1 **Separation Parameters**

In this section I discuss my work adapting the likelihood ratio method of Williams et al. (2019). They calculate the probability of a potential counterpart being the true host based on a spatial separation parameter and the counterpart's magnitude and colour.

Williams et al. (2019) use the separation between the flux density weighted LOFAR catalogue radio position and the position of the possible optical counterpart as the main parameter for assessing the probability of association with a particular galaxy. This method assumes the true radio and optical source positions are the same, and any separation between the radio source and its counterpart is due to statistical uncertainties. In what follows I use the "Centroid distance" to refer to this separation measure; however, as discussed in Section 4.2.4 I relax the underlying assumption regarding the statistical origin of deviation between host and radio centroid to better reflect the nature of extended source behaviour. I use Centroid distance as a comparison to my ridgeline separation measure in the analysis which follows.

The "Ridge distance" is the shortest separation between a possible counterpart and the ridgeline. It is the perpendicular distance determined using the line segment joining the nearest two consecutive ridge points to the possible counterpart. If the perpendicular line from the counterpart lies outside the line segment on the ridgeline, then the distance to the closest ridge point is used. Similar to the original method, the assumption is that within uncertainties the true host should lie on the ridgeline. The SB separation, consisting of the distance of the host to the morphological central feature, i.e., peak or dip, as described previously (see Section 4.1.2) is the third distance parameter which can be considered.
I carried out preliminary testing using only the radio parameters to investigate the performance of the three separation parameters. For my initial investigation of a distance-only likelihood ratio formulations incorporating ridgeline information (i.e., neglecting host parameters such as magnitude and colour) I used the formula of Best et al. (2003). This LR is based purely on the separation of two sources using the formula

$$LR_{\text{test}} = \frac{1}{2\lambda} e^{\lambda \frac{r^2}{2\lambda} - (\lambda - 1)}$$

where \( \lambda = \pi \sigma_a \sigma_\delta \rho \) is the density of objects per arcsec in the optical catalogue, \( r \) is the separation and \( \sigma_a, \sigma_\delta \) are the uncertainties measured in the RA and Dec. The separation \( r \) is given by

$$r = \left( \frac{(\Delta \alpha)^2}{\sigma_\alpha^2} + \frac{(\Delta \delta)^2}{\sigma_\delta^2} \right)^{\frac{1}{2}}$$

where \( \Delta \alpha, \Delta \delta \) are the differences in RA and Dec between the radio position and optical source and \( \sigma_\alpha, \sigma_\delta \) are the uncertainties as before (Richter 1975; de Ruiter et al. 1977; Best et al. 2003). To calculate \( \sigma_\alpha, \sigma_\delta \) the uncertainties from both catalogues and an astrometric uncertainty are combined as follows: \( \sigma_\alpha^2 = \sigma_{\alpha, \text{rad}}^2 + \sigma_{\alpha, \text{opt}}^2 + \sigma_{\alpha, \text{ast}}^2 \), and \( \sigma_\delta^2 = \sigma_{\delta, \text{rad}}^2 + \sigma_{\delta, \text{opt}}^2 + \sigma_{\delta, \text{ast}}^2 \) (as in Williams et al. (2019) \( \sigma_{\text{ast}} = 0.6 \) arcsec was chosen).

For the known hosts in the ridgeline sample the \( LR_{\text{test}} \) from Eq. 4-1 was calculated where the three separations were taken. For the test sample of 950 completed ridgelines 98.2% of the hosts can be found within the 30 closest optical sources to the LOFAR catalogue position. I therefore limited my search for each radio source to the 30 nearest galaxies. For each radio source in the sample the \( LR_{\text{test}} \) was calculated for the 30 nearest optical sources. The potential counterpart with the highest \( LR_{\text{test}} \) for each was compared with the known host. The Centroid \( LR_{\text{test}} \) and Ridge \( LR_{\text{test}} \) for each potential counterpart were combined using the geometric mean to give a Combined \( LR_{\text{test}} \). The counterpart with highest Combined \( LR_{\text{test}} \) was also compared to the known host.

On visually inspecting the outcomes of the \( LR_{\text{test}} \) there were \( \sim 11\% \) of the 950 sources where the most likely candidate chosen was an outlier of the 30 closest sources. Further checking revealed that these sources had high optical errors. Therefore, the optical catalogue was filtered, removing sources with positional
errors > 1 arcsecond in the RA and DEC. To ensure none of the sample hosts were lost in the filtering, the maximum error was checked and is < 0.3 for both RA and DEC. A by-eye check was done on the outcomes with the new optical catalogue and a significant improvement was seen. For the centroid separation 5.6% more of the sample was correctly identified, for the ridge separation 15% more, and for the combined separation 10.2% more.

The number of correctly found hosts with each LR$_{\text{test}}$ is given in Table 4-3, which shows that the Combined LR$_{\text{test}}$ can correctly identify 63.7% of the known hosts. Using just the SB distance 44.9% of the hosts are recovered. The SB LR$_{\text{test}}$ outcomes were multiplied with the Centroid, Ridge or Combined LR$_{\text{test}}$ outcomes before determining a successful identification, see Table 4-3. The combination of ridgeline separation and SB separation successfully identifies 48% of the hosts, an increase from using just the ridgeline separation. The number of hosts identified through combining SB with the Centroid and Combined LR$_{\text{test}}$ outcomes is lower than using each one individually.

Table 4-3 – The percentage of correctly identified hosts for each separation parameter of the ridgeline sample. The centre column shows the percentage of successfully identified hosts using each separation parameter in the LR$_{\text{test}}$ from Best et al. (2003). The final column shows the percentage of correctly identified hosts in combination with the SB LR$_{\text{test}}$ outcomes as discussed in Section 4.2.1.

<table>
<thead>
<tr>
<th>SEPARATION MEASURE</th>
<th>SEPARATION SUCCESSES</th>
<th>SEPARATION AND SB SUCCESSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CENTROID</td>
<td>57.6</td>
<td>55.2</td>
</tr>
<tr>
<td>RIDGE</td>
<td>40.7</td>
<td>48.0</td>
</tr>
<tr>
<td>SB</td>
<td>44.9</td>
<td>-</td>
</tr>
<tr>
<td>COMBINED</td>
<td>63.7</td>
<td>58.0</td>
</tr>
</tbody>
</table>

The ridgeline distance performed less successfully than expected, and so a visual inspection of the potential counterparts with the maximum LR$_{\text{test}}$ and the known hosts was undertaken. The Ridge LR$_{\text{test}}$ is very good at determining the closest potential counterpart to the ridgeline; however, this is not always the host. This led to the use of combining the Centroid and Ridge LR$_{\text{test}}$ outcomes for host determination and motivates the use of magnitude and colour to reject faint unrelated galaxies.
This demonstrates the promise of using a ridgeline-based separation measure and also shows that combining with a radio centroid-based measure shows potential. My tests showed that whilst the ridge distance performed comparably to the centroid distance, the best results were obtained by taking the geometric mean of the two, rather than just taking the possible counterpart with the highest LR\textsubscript{test} using either separation. The SB distance measure performed less well and so has not been applied further; however, its use could be further explored after future code refinements such as smoother profiles and improved peak detection.

### 4.2.2 Application of Magnitude and Colour

Having selected the best separation parameter as a combination of the ridge distance and centroid distance, I am now going to improve RL-XID’s host identification process by applying the additional information of the potential host galaxy’s magnitude and colour.

The combined optical catalogue of Pan-STARRS and AllWISE sources has had no pre-filtering for astronomical objects such as star forming galaxies, or stars. Radio jets are known to be associated with hosts of particular colours and magnitudes, leading Williams et al. (2019) to apply these parameters in their LR.

The LR Williams et al. (2019) used to statistically investigate whether a source observed at one wavelength is the correct counterpart (or host) to a source in another wavelength, is calculated as the ratio of the probability of the source being the correct counterpart over being a random source. This is given by:

\[
LR = \frac{q(m,c)f(r)}{n(m,c)}
\]

where \(q(m,c)\) is the a priori probability of a radio source having a counterpart of magnitude, \(m\), (split into fixed colour bins, \(c\)) and \(n(m,c)\) is the sky density per unit area (\(\text{arcsec}^2\)) of objects at this magnitude (split into the same colour bins, \(c\)). \(f(r)\) is the probability distribution of the offset (Sutherland & Saunders 1992; Williams et al. 2019). As with Williams et al. (2019) the following methods were carried out using PanSTARRS i-band and AllWISE W1 magnitudes and the resulting i - W1 colour.
Generating $q(m, c)$ for my sample cannot be carried out in the same way as Williams et al. (2019). There are two main reasons for this. In all instances they apply magnitude through the use of kernel density estimators (KDEs) (Pedregosa et al. 2011). However, in $q(m, c)$, colour is iteratively applied on the number of successes in each colour bin. This does not work for my sample as it is very small compared to the whole population. Secondly, Williams et al. (2019)’s method is designed to determine the hosts from a full sky catalogue when there is no previously known information. I am working with a sample of 950 known AGN with identified host galaxies whose magnitude and colour information can be used to help build the a priori probability, $q(m, c)$.

4.2.3 CALCULATING $q(m, c)$ AND $n(m, c)$

In order to determine the probability distribution which reflects the true distribution of host properties three alternative routes were considered for $q(m, c)$ and tested using only the magnitudes.

(i) The first method investigated was the original technique by Williams et al. (2019). This searches for sources with matching magnitudes across all nearby sky patches, for all given radio sources. However, Williams et al. (2019) were aiming to crossmatch to the full radio population and the extended sources being studied here may well have a different range of host properties.

(ii) The second distribution was created by selecting the closest optical source to each LOFAR catalogue position. These were selected because ~50% of these are known to be true counterparts, from checking with LGZ. This can help counter any biases from using only the known hosts as it is an almost even divide between both counterparts and the whole population.

(iii) The final distribution was generated from the population of 950 known hosts, as this is the best representation of the host properties of complex, extended sources classified by LGZ. This is likely to give overly good results when applied to the same population, but better reflects the most appropriate approach to take with future LOFAR survey sky areas where we can make use of the improved knowledge developed with LoTSS DR1.
For (ii) and (iii) KDEs (Pedregosa et al. 2011) were generated (Gaussian kernel, bandwidth = 0.2, bin size = 0.05) for both the i-band and the W1-band. Out of all three methods, using the \( q(m) \) in (iii) very slightly outperforms the other two methods by less than 0.5 per cent, and so I adopted option (iii) as this best represents the population of extended sources. Applying colour, a 2D KDE (Gaussian kernel, bandwidth = 0.2, bin size = 0.05) was generated for the known hosts of DR1 in colour and magnitude for both the i-band and W1 band and were used as \( q(m,c) \).

Due to the large number of sources in the optical catalogue, a random sample of 50 000 were selected to form a 2D KDE (Gaussian kernel, bandwidth = 0.2, bin size = 0.05) for colour and magnitude in both bands for \( n(m,c) \). Multiple samples were run and checked to make sure they maintained the same properties.

### 4.2.4 Separation Probability Function

Williams et al. (2019) define \( f(r) \) as the probability distribution of the offset between the optical source and the flux density weighted LOFAR catalogued position. I have taken \( f(r) \) to have the form:

\[
f(r) = \frac{1}{2\pi \sigma^2} e^{-\frac{r^2}{2\sigma^2}},
\]

where \( r \) is the separation to the potential counterpart and \( \sigma \) is the uncertainty on this separation. Using the previous distance-based investigations the best results were achieved through taking the geometric mean of the \( f(r) \) of the centroid distance and the ridgeline distance. I therefore tested the magnitude and colour LR formulation with the outcomes of \( f(r) \) for each of the ridgeline and centroid distance definitions separately. Note that the formally correct distribution for the ridgeline distance parameter is a 1D rather than 2D Gaussian. The method performance for the Ridge distance is not found to differ significantly if a 1D or 2D Gaussian distribution is used.

For the Ridge separation, maintaining the assumption that the host will lie on the ridgeline within positional uncertainties gives \( \sigma^2 = \sigma_{\text{rad}}^2 + \sigma_{\text{opt}}^2 + \sigma_{\text{ast}}^2 \). The astrometric uncertainty between the optical and radio catalogues was chosen to be \( \sigma_{\text{ast}} = 0.6 \) arcsec from Williams et al. (2019), the optical positional uncertainty for each source, \( \sigma_{\text{opt}} \), is taken from the optical catalogue and, after extensive
testing, we took $\sigma_{\text{rad}}$ to be 3 arcsec (2 pixels). The choice of $\sigma_{\text{rad}}$ is related to the step and sector size ($R$ and $d\phi$) and is the optimal setting for the LR given the systematic uncertainties producing some of the issues discussed in Section 3.4.1.1.

For the Centroid separation, as $\sigma$ represents the assumed width of the distribution of the separation, $r$, I used the known distribution of catalogue/host offsets for extended sources from LOFAR DR1 to derive empirically that $\sigma = 0.2$ in units of the source size (i.e., the host is typically within the central 40% of the radio source extent). This empirically derived distribution better accounts for the known broad distribution of the centroid position host offsets, with the centroid separation taken as the distance from the possible counterpart to the LOFAR catalogue position as a fraction of the size of the source as given by Mingo et al. (2019). My method emphasises the possible counterparts which are within the size of the source, whilst reducing the impact from those further out.

As I am matching this set with the known hosts from LGZ, all of which have AllWISE identifications, I chose to use only the W1 magnitude as a parameter in Eq. 4-3. In LGZ many instances were found where an AllWISE source was present in the expected location of a host, particularly for small double radio sources, but no PanSTARRS source was present. I have chosen to use the W1 magnitude because it is more likely that a counterpart will exist in this band (Sabater et al. 2019). This may need adjusting for future datasets where there is the possibility of detection in different bands.
4.2.5 **OUTCOME OF THE NEW LIKELIHOOD RATIO METHOD**

The magnitude and colour based LR optical identification process was run for the three separations discussed above: the centroid, ridgeline and combined separation parameters, with the results shown in Table 4-4. It is clear that both separation parameters perform well individually. The maximum number of correct hosts which can be found for the large and bright sources ($S > 15$ mJy and $\theta > 60$ arcsec) is 95.5% of the ridgeline sample or 91.5% of the full group. This number is obtained via the combination of both separations, with 816 correctly identified by both separations, 38 correctly identified by the centroid separation alone and the 54 identified by the ridgeline separation alone. This demonstrates that automated methods of source identification can be very successful for extended sources. Table 4-4 demonstrates that the combination of the ridgeline and centroid, where the geometric mean of the distance probability functions was taken before the LR was calculated, successfully identifying 92.4% of hosts. For future datasets in which the true hosts are not known, this method is most suitable as it does not need prior information about which distance parameter will perform best.

Having established the success of the cross-identification method, I tested it on a wider range of flux densities and source sizes. RL-XID was applied to all sources in the Hardcastle et al. (2019) AGN catalogue which satisfy the criteria of a flux density $> 10$ mJy and a size $> 15$ arcsec. There are 3964 sources meeting these requirements, of which RL-XID successfully drew ridgelines for 3384 (85.4%) sources. The LR was then calculated for these 3384 sources using the different separations and colour and magnitude information in the same way as for the large, bright source sample. The results are also shown in Table 4-4.
Table 4-4 - The percentage of correctly identified hosts in the sample sets obtained using the Centroid and Ridge separations, the combination of both, and the union of both. The results are split into three sections: the original large and bright group (*Left most columns*) those with a size over 60 arcsec and flux density greater than 30 mJy; the full DR1 sample (*Right most columns*) everything over 15 arcsec and 10 mJy; and those of an intermediate size and flux density (*Central two columns*). The results are given first as a percentage of successes from the number of successfully drawn ridgeline sources in each category, and secondly as a percentage of all the sources in the category.

<table>
<thead>
<tr>
<th>SEPARATION</th>
<th>( S &gt; 30 ) mJy and ( \theta &gt; 60 ) arcsec (950 sample)</th>
<th>( 10 ) mJy &lt; ( S &lt; 30 ) mJy and ( 15 &lt; \theta &lt; 60 ) arcsec</th>
<th>( S &gt; 10 ) mJy and ( \theta &gt; 15 ) arcsec (Full DR1 AGN set)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Ridgelines</td>
<td>% Group Total</td>
<td>% Ridgelines</td>
</tr>
<tr>
<td>CENTROID</td>
<td>89.8</td>
<td>86.1</td>
<td>97.8</td>
</tr>
<tr>
<td>RIDGE</td>
<td>91.5</td>
<td>87.7</td>
<td>96.8</td>
</tr>
<tr>
<td>COMBINED</td>
<td>92.4</td>
<td>88.6</td>
<td>98.0</td>
</tr>
<tr>
<td>UNION</td>
<td>95.5</td>
<td>91.5</td>
<td>99.0</td>
</tr>
</tbody>
</table>
I used the combination of the results from the different separation parameters in conjunction with the host galaxies properties to produce a success rate of 98.0% of correct host galaxies found. This can be attributed to the slightly smaller sized sources than the original sample having a smaller population of nearby galaxies from which to select possible counterparts. This is demonstrated in the centre two columns of Table 4-4, where the number of hosts found, as a percentage of the ridgelines drawn, is 99.0% in the AGN catalogue. These are the intermediate sources which satisfy the criteria of having a flux density between 10 and 30 mJy and a size between 15 and 60 arcsec.

As this method will be applied to datasets with no prior hosts determined, I also compare the combined Centroid and Ridge separation results directly with the performance of the previous host identification methods from Williams et al. (2019) for DR1. In the full DR1 sample of 3946 sources, 33.7% (1331) were previously identified using Williams et al. (2019)'s original LR. Of the 3384 where the ridgelines successfully drew, 28.7% (971) were already identified through their LR method. For the 3263 where the hosts were correctly identified through RL-XID, 29.6% (965) were already known. For the remaining 121 unidentified ones, 5.0% (6) were already identified. In summary, RL-XID was able to identify an additional 58.2% (2298) hosts in the selected full AGN sample compared to the LR in Williams et al. (2019).

Of the 562 AGN meeting the size and flux density requirements, for which ridgelines could not be drawn, most failed due to catalogue errors or the sources being circular and centre bright. This structure is ideal for identification through the original LR method and indeed 64.1% (360) of these hosts have already been identified in this way, and it is therefore unlikely that these sources would need to be identified using RL-XID. For the remaining sources where a ridgeline could not be drawn, using the centroid is a viable method for determining counterparts.
4.3 SUMMARY

In LoTSS DR1 a likelihood ratio method was used to determine the majority of IR/optical counterparts. This statistical determination works very well for small, compact sources. However, for larger, extended sources or those with a more complicated structure, for example, where blending of multiple sources may occur, the citizen science project LOFAR Galaxy Zoo was used to determine the host galaxies.

As an alternative to this labour-intensive process, I have developed RL-XID to draw ridgelines and perform cross-identification for extended radio sources. This method requires a given radio catalogue with correctly associated radio components for the non-single component sources. In the full DR1 sample ~76% (2984) of the sources were considered to be single component sources, therefore at least 25% of sources would have to be associated. In this chapter I have demonstrated:

(i) RL-XID was able to draw ridgelines on 85.8% of the LoTSS DR1 sample of sources over 10 mJy and 15 arcsec, including 95.9% of the sources over 30 mJy and 60 arcsec.

(ii) Of the ridgeline sample group for the largest and brightest sources (over 30 mJy and 60 arcsec), RL-XID was able to correctly identify 95.5% of the hosts, using the union of the Centroid and Ridge distance parameter results for the likelihood ratio function. For the full LoTSS DR1 ridgeline sample, using the same method, 98.0% were correctly identified.

(iii) The fainter (between 10 and 30 mJy) and smaller (between 15 and 60 arcsec) source subset had 99.0% hosts correctly identified, mostly likely due to a smaller possible optical population surrounding the source.

(iv) I have shown that the most successful method to be applied to a new dataset for which hosts are unknown is the combined Centroid and Ridge probability distribution function for separation: the likelihood ratio found 82.7% of the full DR1 sample hosts, where the previous likelihood ratio method had found 33.7%. RL-XID identified 49.0% more hosts, significantly reducing the number of possible sources requiring cross-identification via LGZ, though association will still need to be performed. This proportion could be increased by applying the centroid distance parameter only in cases where a ridgeline could not be drawn.
Preliminary results demonstrate the effectiveness of surface brightness profiles as a complementary method of automated morphological classification which is well matched to the outcomes of LoMorph (Mingo et al. 2019).

This method shows the potential of automated methods for cross-identification to be applied to extended sources. The intention is for this method to be used in conjunction with the already existing LR method for DR2 of LoTSS to help identify IR/optical counterparts and reduce the number of sources requiring classification via the public LGZ. The testing of RL-XID was carried out on data with known hosts and pre-associated sources, so minor improvements were applied when run on the LoTSS DR2 dataset. This includes a LR threshold, chosen to reject objects with no visible host, and code performance improvements, as more information about the true distribution of the host properties is incorporated. In Chapter 6 I discuss preliminary testing of RL-XID on the LOFAR DR2 which is already showing good performance results.
5 REVEALING THE PHYSICS OF A LOW-LUMINOSITY FRII POPULATION

"Fun isn’t something one considers when balancing the Universe. But this... does put a smile on my face."

Thanos,
Marvel’s, Avengers: Infinity War

There are two traditional morphological classes for extended radio galaxies, FRI which are centre bright, and FRII, whose brightness peaks at the edges, where jets can terminate in hotspots (Fanaroff & Riley 1974) (see Section 1.4). Amongst other properties, FRIs and FRIIs have been traditionally classified through luminosity. Fanaroff & Riley (1974) recognised a break in luminosity such that FRIIs were found to be more luminous than FRIs. However, a population of low luminosity FRIIs has been identified in recent radio surveys. For example, Mingo et al. (2019) found ~51% of FRIIs in LoTSS are below the traditional break luminosity. This chapter describes a VLA follow-up survey of a sample of these low-luminosity FRIIs.

Section 5.1 introduces the background to this project, covering the traditional luminosity break and why a population of low-luminosity FRIIs is interesting. The sample of 19 sources is described in Section 5.2. This covers how the sample was selected, observed, and processed. The full details of the data processing can be found in Section 2.3. The final output of these steps is a set of images that can be found in Section 5.3 along with the original LoTSS images and comparative FIRST images. This section also includes the images from a comparison sample of traditional high luminosity FRIIs, as well as a discussion about how representative each sample is of its parent population.

Section 5.4 discusses the results. There is a comparison of morphology, integrated spectral indices, and possible links between radio structure, luminosity, and host galaxy magnitude. This is concluded with a section determining if there are any possible remnant or restarter candidates. My overall findings are summarised in Section 5.5.
5.1 INTRODUCING THE FRI/FRII BREAK

Traditionally RLAGN are morphologically split into two FR classes (Fanaroff & Riley 1974) often interpreted as linked to the jet’s interactions with the environment. As well as the luminosity break identified by Fanaroff & Riley (1974), FRIs are described as low-luminosity, centre bright jets, that have been disrupted by their surroundings and decelerated within a few kpc. In comparison the higher luminosity FRIIs have jets that remain relativistic throughout, are edge brightened, and terminate in a hotspot (internal shock) (Bicknell 1995; Laing and Bridle 2002a; Tchekhovskoy & Bromberg 2016). It is thought that this structural difference is caused by the interplay between jet power and environment density, meaning that equally powered jets will disrupt easier in richer environments producing FRIs (Bicknell 1995; Kaiser & Best 2007). Ledlow & Owen (1996) provide support for the theory that the FR luminosity break is dependent on host-galaxy magnitude. They found that FRIs were likely to have higher luminosities in brighter host galaxies, where the interstellar medium is assumed to be denser. However, the limited samples leading to selection effects, such as varied redshift distributions and environments of the FRIs and FRIIs, has led to debate over whether this is true for the whole population (Best 2009; Lin et al. 2010; Wing & Blanton 2011; Singal & Rajpurohit 2014; Capetti et al. 2017; Shabala 2018). As well as the standard model, based on jet dynamics and environmental interactions, there is ongoing work into the links between accretion mode and jet morphology (Hardcastle et al. 2007, 2009; Best & Heckman 2012; Gendre et al. 2013; Mingo et al. 2014; Tadhunter 2016; Hardcastle 2018)

Most of our previous knowledge comes from higher flux density surveys, such as the 3C catalogue (Mackay 1971). A more comprehensive view of RLAGN is being built up from recent deep, wide-area surveys (Norris et al. 2011; Jarvis et al. 2016; Hurley-Walker et al. 2017; Shimwell et al. 2019) by exploring the distant, faint, and low surface-brightness radio population. These surveys are reducing the bias of earlier studies and have demonstrated an overlap in luminosity between those sources with FRI and FRII morphology rather than a clear luminosity break (Best 2009; Miraghaei & Best 2017; Mingo et al. 2019). These surveys are also revealing more extensive extended source population at low surface brightness (Brienza et al. 2016, 2017; Kapińska et al. 2017; Mahatma et al. 2018, 2019; Mingo et al. 2019) indicating that a simple separation of FRI/FRII could be missing subtler distinctions.
Using the LOFAR Two Metre Sky Survey Data Release 1 (LoTSS DR1) at 150 MHz (Shimwell et al. 2019) Mingo et al. (2019) discovered a large population of FRIIs with luminosities up to 3 magnitudes lower than the typical FR break \(L_{150} = 10^{26} \text{ W Hz}^{-1}\). These FRII-lows are thought to be composed of two different populations; those which are likely to be older FRIIs fading in luminosity from their peak, and many which are hosted by lower mass galaxies. These have likely been unobserved in previous studies due to their rarity and the higher flux limit of the surveys (Mingo et al. 2019).

A population of low-luminosity FRIIs raises many questions. For example, if there exists a population of low-luminosity AGN with FRII source dynamics, then the FR break model predicts that they must have differing host/environment properties to FRIs at similar luminosities (e.g., lower ambient gas density). As previously mentioned, this will also lead to questions as to whether low-luminosity FRIIs will have similar or different triggers to the general low-luminosity population (Tadhunter 2016; Hardcastle 2018). Low-luminosity FRIIs also have implications for jet power and the environmental impact of low-luminosity sources. This is due to the different particle content associated with FRI-like and FRII-like jet dynamics, affecting the conversion of radio luminosity to jet power (e.g., Croston et al. 2005, 2018).

However, if low-luminosity FRIIs do not have the same dynamics as powerful FRIIs, then attempts to apply FR classifications to deep, wide-area surveys (e.g., Alhassan et al. 2018) will lead to categories which will be difficult to use to provide reliable conclusions about physical behaviour. Therefore, in order to accurately infer relationships between black-hole and galaxy evolution using large samples of RLAGN from current and upcoming surveys, an understanding of the structure and dynamics of low-luminosity FRIIs needs to be developed. It is possible that the traditional classification of FRI/FRII needs to be reconsidered before being applied generically across large surveys at differing frequencies.
5.2 The VLA Sample Set

At 150 MHz LoTSS is currently the most sensitive wide-area survey. Its $uv$-coverage allows it to be sensitive to large scale sources as well as having good angular resolution (see Section 2.1.1). It is from this dataset of comparatively low resolution, low frequency radio images that Mingo et al. (2019) identified an apparent population of edge-brightened (FRII-like) sources with $L_{150} < 10^{25}$ W Hz$^{-1}$, far below the expected FRI/FRII boundary. This population motivates the need to study a sample of these sources further via observations using the VLA. I have used higher frequency, higher resolution images of a sample of low-luminosity FRII sources to compare the morphological properties and spectral features of the low-luminosity FRIIs with well-studied luminous FRIIs.

A sample of Mingo et al.’s (2019) FRII-lows was selected to be observed using the VLA (see Section 2.2). By using observations in the L- and C-bands with a combination of the A, B and C configurations my aim in this chapter was to obtain higher frequency, higher resolution images of a sample of the FRII-lows, with which to reveal the dynamics of the low luminosity FRIIs and confirm if these sources have true FRII dynamics. I have done this through detecting and mapping their compact features, confirming the prevalence of hotspots, cores, and possibly jets.

These sources are taken from LoTSS DR1 (Shimwell et al. 2019), and therefore they have host identifications from PANSTARS/WISE given by Williams et al. (2019) (see Sections 2.1.3 and 4.2), and $z < 0.8$. To select the sample sources, they are classified as FRIIs, where their FR classification has been performed previously by LoMorph (see Section 4.1.2). This has a >95% reliability for FRII classifications (compared to visual inspection) and is described in detail by Mingo et al. (2019). The sources were chosen to have $L_{150} < 10^{25}$ W Hz$^{-1}$, $S_{150} > 10$ mJy and an angular size $\theta > 50$ arcsec. The sample was selected using the adjusted size, flux, and luminosity values as described in Section 2.5 of Mingo et al. (2019) (see also Section 2.1), compared to the catalogued LoTSS values. As the traditional break is at $L_{150} = 10^{26}$ W Hz$^{-1}$ my sample is chosen to be well below this (Fanaroff & Riley 1974; Ledlow & Owen 1996). This generated a sample of 20 sources with luminosities ranging from $5 \times 10^{23} - 10^{25}$ W Hz$^{-1}$. These luminosities are based on distances obtained using spectroscopic redshifts for 75% of the sample (including two of the lowest luminosity sources) and photo-$z$’s for the rest of the sample (Duncan et al. 2019). This gives a sample
comprising ~9% of the whole population. The distribution of HERGs and LERGs in the sample is unknown, however, Mingo et al. (2022)’s recent work on the LOFAR deep fields indicates that the FRII-low population has a high proportion of LERGs.

More recently LoMorph has been run on the same dataset but with the better quality DR2 images. The VLA target sample of 19 sources was selected on the outcome of LoMorph on the DR1 images from LoTSS, and the re-run reclassified 9 of the sources in the sample. The sources are still edge brightened, however due to small changes in the imaging quality for DR2 they no longer meet LoMorph’s formal criteria for FRII classification. As they are not members of the full Mingo et al. (2019) FRII population there may be a selection bias affecting the some of the results. The properties of the sources are summarised in Table 5-1.

The observations of the 19 sources in the sample (one was not observed, due to time constraints) were taken over four sessions during March to August 2019 (see Section 2.2.1 for observation details). The sources were observed in the L and C bands using the A, B and C configurations. In the L band all the sources were observed in the A and B configurations, and 13 were observed in the C configuration, and in the C band all the sources were observed in the B configuration. Full observation details are summarised in the final column of Table 5-1. The final images presented are formed from the L band A and B configurations. The reduction and imaging of the C band observations will form part of a future project. The combination of the A and B configurations, at a resolution of 1.3 arcsec, has sufficient surface brightness sensitivity for hotspots and extended emission to be visible. The detection (or non-detection) of hot spots will establish what fraction of my sample (and hence population) have true FRII source dynamics.
Table 5-1 – The properties of the FRII-low sample. The columns are 150 MHz luminosity density, redshift, angular size, physical size, and host galaxy magnitude. The luminosity, angular and linear size are those as calculated by Mingo et al. (2019) and the host galaxy K$_s$-magnitudes are those given by Duncan et al. (2019). The final column gives the configurations of the VLA the sources were observed in the L band with.

<table>
<thead>
<tr>
<th>LOTSS SOURCE NAME</th>
<th>LUMINOSITY ($\times 10^{24}$ W Hz$^{-1}$)</th>
<th>REDSHIFT</th>
<th>ANGULAR SIZE (arcsec)</th>
<th>LINEAR SIZE (kpc)</th>
<th>HOST MAGNITUDE (K$_s$)</th>
<th>C CONFIGURATION OBSERVATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILTJ105946.75+563136.4</td>
<td>8.4</td>
<td>0.18</td>
<td>61.8</td>
<td>189.7</td>
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<td>-</td>
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<td>ILTJ112015.05+503254.9</td>
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<td>0.09</td>
<td>84.9</td>
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<td>-</td>
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<td>73.0</td>
<td>130.9</td>
<td>-22.84</td>
<td>-</td>
</tr>
<tr>
<td>MEDIAN</td>
<td>5.8</td>
<td>0.17</td>
<td>84.9</td>
<td>311.9</td>
<td>-23.26</td>
<td>-</td>
</tr>
</tbody>
</table>
I also made use of images tapered to the LoTSS resolution of 6 arcsec for a preliminary investigation of lobe spectral properties. The largest angular size (LAS) on the B configuration is 60 arcsec because observations are short. The C configuration has a larger LAS and can therefore detect any emission that is over 60 arcsec that the VLA would otherwise be blind to in the B configuration. For those sources observed in the L band C configuration, nine of the 13 have sufficiently large angular size that the addition of the C configuration data may have a significant effect on the flux measurements. However, the main focus of my work is on the compact features, for which the A and B configurations are best suited. There was not enough time during the scope of this work to incorporate the C configuration observations, however I have commented on the impact of including them where relevant.

As described in detail in Section 2.3 the data reduction was carried using NRAO’s CASA software version 5.7.0-134 (McMullin et al. 2007) During the data reduction the RFI was removed both manually, and automatically with the tfcrop and rflag procedures. The flux density scale for the flux calibrator was determined using the Perley & Butler (2017) 3C 286 model. Each source required a calibrator source for the data reduction process, and this is listed in the second column of Table 5-2. In the case of ILTJ114351.49+511712.6 two different calibrators were used; J1219+4829 for the A configuration and J1035+5628 for the B configuration. After calibration was completed statwt was used to find the weightings of the A and B configuration data, based on their RMS, allowing them to be successfully combined for imaging.

The combined A and B configuration uv files were imaged using tclean with a multiscale deconvolver (Cornwell 2008), and a Briggs weighting (Briggs 1995) with robust = 0. The value for the robust was selected after careful investigation to determine the optimal value for image dynamic range and ability to see hotspot detail. As these observations were performed at lower frequencies, the wide-field imaging parameter (w-projection) was applied. The integration time is 2 secs for the A configuration and 3 secs for the B configuration, and each spectral window of width 0.06 GHz is divided into 14 averaged channels. The bandwidth and time interval smearing do not have a significant effect on the inner 28 arcmin where the sources are found.

The details for the final images are given in Table 5-2. Out of these 19 sources, 13 are well detected in the VLA maps. Of the remaining six, two have very faint detections and four did not yield a detection in the VLA observations (these have
been marked in Table 5-2 with a +). These six are identified in the shaded rows of the table. For the four sources where there is no detection, two (ILTJ112015.05+503254.9 and ILTJ114351.49+511712.6) have marginal detections in FIRST. They have very clear, bright sources nearby that could have flux levels high enough that even with thorough calibrating and cleaning of the VLA observation data the low luminosity sources have not been detected. The remaining two non-detections (ILTJ134315.98+553139.6 and ILTJ145936.33+484219.8) may be the result of the high amount of RFI flagging that was required through the calibration process, making the SNR too low to detect the source. However, as both sources are also not detected in FIRST, there is the possibility that, combined with high flagging, they may well have too low surface brightness at 1.5 GHz to be fully detected by the VLA as well.

From the observational status summary for 2019A\textsuperscript{38} the theoretical thermal noise of an image is given by:

$$
\Delta I_m = \frac{SEFD}{\eta_c \sqrt{n_{pol} N(N-1)t_{int}\Delta v}}
$$

Eq. 5-1

where:

- \(SEFD = 420\) Jy for the L band and is defined as the flux density of a radio source that doubles the system temperature
- \(\eta_c = 0.93\) and is the correlator efficiency
- \(n_{pol} = 2\) and is the number of polarisation products included in the image. As these are Stokes I images this is equal to 2
- \(N = 26.75\) and is the number of antennas used. Across four observing periods a mix of 26 and 27 antennas were used so an average was taken
- \(t_{int} = \) total time on source, and is given by the sum of all time taken over each of the four observing sessions
- \(\Delta v = 1 \times 10^9\) Hz and is the bandwidth of the observations. These spanned the full 1 – 2 GHz (17 spw) of the L band. In some datasets full spectral bands were flagged (see Section 2.3.2) so the bandwidth is lower than this, however for simplicity, this is not accounted for in the table

The calculated results are given in the table. They can be compared with the observed noise levels to give an indication of the quality of the data reduction and whether self-calibration could be a possible next step. For all of the sources

\textsuperscript{38} https://science.nrao.edu/facilities/vla/docs/manuals/oss2019A/performance/sensitivity
self-calibration was theoretically possible. I tested this on a couple of sources with brighter cores, and those with poor detections due to brighter sources nearby. There was a minor increase in the numerical quality of the image when comparing the dynamic range and noise, however there was no visually obvious improvement in image quality. Therefore, none of the images have been self-calibrated.

The observed noise levels (rms) and maximum (peak) flux value in the image were obtained using `imstat`. They are used to calculate the dynamic range (the ratio of peak flux to observed rms). The dynamic range can also be an indicator of the quality of the final image, as it provides a numerical representation of the contrast between the source emission in the image and the background noise. Included with this is a ratio of the observed to the theoretical rms. The majority of the maps have a noise level within four times the theoretical noise, and for most of the maps this is \( \sim 2.5 \times 10^{-5} \text{ Jy/beam} \). The theoretical noise calculation assumes a natural weighting and is therefore expected to be \( \sim 50\% \) lower than the observed noise using a Briggs with robust = 0 weight. Therefore the true performance is closer to the theoretical expectation than indicated. The dynamic range varies from roughly 100 to 1400 across all the maps.
Table 5–2 – Details of the FRII-Low final images. The first two columns give the LoTSS identifier number and the calibrator(s). The following columns contain the image statistics for the combined VLA observations. These include the total time spent observing the source, both the theoretical and observed RMS levels, and the peak flux of the image. The final two columns give the dynamic range and the ratio of the RMS levels (observed/theoretical). * Source ILTJ114351.49+511712.6 had a different calibrator for the A Configuration (J1219+4829) and the B Configuration (J1035+5628). † The sources which are non-detections with the VLA and are described in the text.

<table>
<thead>
<tr>
<th>LOTSS SOURCE NAME</th>
<th>CALIBRATOR</th>
<th>TIME ON SOURCE (s)</th>
<th>THEORETICAL NOISE (Jy/beam)</th>
<th>OBSERVED RMS (Jy/beam)</th>
<th>PEAK FLUX (Jy/beam)</th>
<th>DYNAMIC RANGE</th>
<th>RMS RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILTJ105946.75+563136.4</td>
<td>J1035+5628</td>
<td>2314</td>
<td>$8.00 \times 10^{-6}$</td>
<td>$8.42 \times 10^{-5}$</td>
<td>0.11</td>
<td>1340.6</td>
<td>10.5</td>
</tr>
<tr>
<td>ILTJ112015.05+503254.9†</td>
<td>J1035+5628</td>
<td>2590</td>
<td>$7.56 \times 10^{-6}$</td>
<td>$3.43 \times 10^{-5}$</td>
<td>0.048</td>
<td>1398.5</td>
<td>4.5</td>
</tr>
<tr>
<td>ILTJ112654.44+540415.3</td>
<td>J1035+5628</td>
<td>2274</td>
<td>$8.07 \times 10^{-6}$</td>
<td>$2.52 \times 10^{-5}$</td>
<td>0.0027</td>
<td>109.3</td>
<td>3.1</td>
</tr>
<tr>
<td>ILTJ114351.49+511712.6†</td>
<td>J1035+5628* J1219+4829*</td>
<td>2418</td>
<td>$7.82 \times 10^{-6}$</td>
<td>$9.85 \times 10^{-5}$</td>
<td>0.11</td>
<td>1103.4</td>
<td>12.6</td>
</tr>
<tr>
<td>ILTJ115011.27+534320.9</td>
<td>J1219+4829</td>
<td>2276</td>
<td>$8.07 \times 10^{-6}$</td>
<td>$3.21 \times 10^{-5}$</td>
<td>0.012</td>
<td>358.4</td>
<td>4.0</td>
</tr>
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<td>ILTJ121623.58+524409.4</td>
<td>J1219+4829</td>
<td>2380</td>
<td>$7.89 \times 10^{-6}$</td>
<td>$2.82 \times 10^{-5}$</td>
<td>0.0083</td>
<td>295.1</td>
<td>3.6</td>
</tr>
<tr>
<td>ILTJ130109.83+560623.4</td>
<td>J1219+4829</td>
<td>2590</td>
<td>$7.56 \times 10^{-6}$</td>
<td>$2.62 \times 10^{-5}$</td>
<td>0.0047</td>
<td>181.0</td>
<td>3.5</td>
</tr>
<tr>
<td>ILTJ130605.63+555127.6</td>
<td>J1349+5341</td>
<td>2494</td>
<td>$7.70 \times 10^{-6}$</td>
<td>$2.20 \times 10^{-5}$</td>
<td>0.0033</td>
<td>148.3</td>
<td>2.9</td>
</tr>
<tr>
<td>ILTJ133217.44+484221.7</td>
<td>J1349+5341</td>
<td>2314</td>
<td>$8.00 \times 10^{-6}$</td>
<td>$2.04 \times 10^{-5}$</td>
<td>0.0021</td>
<td>103.1</td>
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<td>------</td>
</tr>
<tr>
<td><strong>ILTJ133729.25+481822.3</strong></td>
<td><strong>J1349+5341</strong></td>
<td>2238</td>
<td>$8.13 \times 10^{-6}$</td>
<td>$4.08 \times 10^{-5}$</td>
<td>0.040</td>
<td>979.3</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>ILTJ134315.98+553139.6</strong></td>
<td><strong>J1349+5341</strong></td>
<td>2460</td>
<td>$7.76 \times 10^{-6}$</td>
<td>$2.15 \times 10^{-5}$</td>
<td>0.0066</td>
<td>307.2</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>ILTJ135152.95+521618.8</strong></td>
<td><strong>J1349+5341</strong></td>
<td>2450</td>
<td>$7.77 \times 10^{-6}$</td>
<td>$1.95 \times 10^{-5}$</td>
<td>0.0036</td>
<td>183.0</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>ILTJ135630.51+555245.1</strong></td>
<td><strong>J1349+5341</strong></td>
<td>2584</td>
<td>$7.57 \times 10^{-6}$</td>
<td>$2.25 \times 10^{-5}$</td>
<td>0.011</td>
<td>469.3</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>ILTJ144644.12+492012.3</strong></td>
<td><strong>J1549+5038</strong></td>
<td>2592</td>
<td>$7.56 \times 10^{-6}$</td>
<td>$4.65 \times 10^{-5}$</td>
<td>0.041</td>
<td>871.2</td>
<td>6.2</td>
</tr>
<tr>
<td><strong>ILTJ144650.49+514625.3</strong></td>
<td><strong>J1549+5038</strong></td>
<td>2418</td>
<td>$7.82 \times 10^{-6}$</td>
<td>$2.39 \times 10^{-5}$</td>
<td>0.0023</td>
<td>96.0</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>ILTJ145759.29+490219.2</strong></td>
<td><strong>J1549+5038</strong></td>
<td>2516</td>
<td>$7.67 \times 10^{-6}$</td>
<td>$2.45 \times 10^{-5}$</td>
<td>0.0069</td>
<td>280.5</td>
<td>3.2</td>
</tr>
<tr>
<td><strong>ILTJ145936.33+484219.8</strong></td>
<td><strong>J1549+5038</strong></td>
<td>2574</td>
<td>$7.58 \times 10^{-6}$</td>
<td>$4.79 \times 10^{-5}$</td>
<td>0.034</td>
<td>719.6</td>
<td>6.3</td>
</tr>
<tr>
<td><strong>ILTJ150827.77+541507.1</strong></td>
<td><strong>J1549+5038</strong></td>
<td>2272</td>
<td>$8.07 \times 10^{-6}$</td>
<td>$2.62 \times 10^{-5}$</td>
<td>0.0038</td>
<td>143.4</td>
<td>3.3</td>
</tr>
</tbody>
</table>
5.3 THE FINAL IMAGES

Having selected the sample, processed the data, and produced the images as previously discussed, the final images were produced in FITS format. These were inspected using DS9, and images produced in Python using AplPy (Robitaille & Bressert 2012; Robitaille 2019). This section contains the final images produced in Python by AplPy of the FRII-lows, and a comparison group of FRII-highs.

Section 5.3.1 contains all of the FRII-low images from LoTSS, the VLA and FIRST, along with a description of the image details. Section 5.3.2 contains the details of an FRII-high comparison group. This group has been selected at random from Mingo et al. (2019)’s high luminosity FRIIs to act as a comparison set when investigating the source dynamics of the FRII-lows.

5.3.1 FRII–LOWS

The full set of FRII-low images are in Figure 5-1. The original 19 LoTSS 150-MHz 6 arcsec resolution images are in the left-most column. Their properties are given in Table 5-2. The central column contains the corresponding new VLA images, produced after the data reduction and image cleaning processes described in Section 2.3 and Section 5.2. These are at a frequency of 1.5 GHz and have a resolution of 1.3 arcsec and are the result of combining both the A and B configurations in the L band. When generating the images, the pixel to arcsecond ratio was chosen to match the A configuration and to over sample the B configuration. This produced images at 1.3 arcsec resolution and allows for the compact features such as hotspots and cores to be observed in more detail.

To complete the comparison the images from FIRST are included (Figure 5-1). These 1.4 GHz, 5 arcsec images are in the right-most column. These were included as a comparison to see if the VLA images meet the expected outcomes of the higher frequency observations. FIRST has a higher detection threshold and lower resolution, and the VLA observations should pick up some features not seen in the FIRST images.
LoTSS  
VLA  
FIRST

(a) ILTJ105946.75+563136.4

(b) ILTJ112015.05+503254.9

(c) ILTJ112654.44+540415.3

(d) ILTJ113626.52+501320.3
Figure 5-1 – The images of the FRII-lows. In the lefthand column are the original LoTSS 150 MHz, 6 arcsec resolution images, in the central column are the 1.5 GHz, 1.3 arcsec resolution VLA images, and in the righthand column are the FIRST 1.4 GHz 5 arcsec resolution images. The LoTSS source names are given under each set of three comparison images.
5.3.2  **FRII – HIGHS**

To carry out a full investigation into the FRII-lows I defined a sample of high-luminosity FRIIs (FRII-highs). The intention is to have a comparison sample of the well-studied luminous FRIIs, which have formed the basis of the studies of FRII physics, dynamics, and energetics to date. These ten sources were selected at random from Mingo et al.’s (2019) sources classified as FRIIs with $L_{150} > 10^{26}$ W Hz$^{-1}$ and make up ~5% of the population of FRII-highs. The properties of these sources are given in Table 5-3. For these the 6 arcsecond LoTSS images were extracted, along with the FIRST images to help in identifying hotspot features (see Figure 5-2). The images were created to provide an example of the FRII-high population in both low and high frequencies, and to act as a comparison group for the FRII-lows. As only FIRST images are available, the angular resolution is lower, but because the sources have higher flux than the FRII-lows their structure is generally very well mapped.
Table 5-3 – The properties of the FRII-high sample data set. The columns are luminosity, redshift, angular size, physical size, and host galaxy magnitude. The luminosity, angular and linear size are those as calculated by Mingo et al. (2019) and the host galaxy $K_s$-magnitudes are those given by Duncan et al. (2019). The luminosities are in the same units as the FRII-low table to allow their higher luminosities to be easily compared. The final row gives the median value for each feature.

<table>
<thead>
<tr>
<th>LOTSS SOURCE NAME</th>
<th>LUMINOSITY ($\times 10^{24}$ W Hz$^{-1}$)</th>
<th>REDSHIFT</th>
<th>ANGULAR SIZE (arcsec)</th>
<th>LINEAR SIZE (kpc)</th>
<th>HOST MAGNITUDE ($K_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILTJ104706.09+534417.1</td>
<td>922.8</td>
<td>0.64</td>
<td>93.9</td>
<td>656.8</td>
<td>-23.91</td>
</tr>
<tr>
<td>ILTJ111531.16+560051.2</td>
<td>125.0</td>
<td>0.58</td>
<td>145.3</td>
<td>968.4</td>
<td>-24.09</td>
</tr>
<tr>
<td>ILTJ114558.65+512530.6</td>
<td>421.0</td>
<td>0.57</td>
<td>60.3</td>
<td>398.6</td>
<td>-23.64</td>
</tr>
<tr>
<td>ILTJ121847.62+502609.5</td>
<td>336.8</td>
<td>0.20</td>
<td>212.9</td>
<td>708.2</td>
<td>-23.88</td>
</tr>
<tr>
<td>ILTJ125805.10+541704.4</td>
<td>134.5</td>
<td>0.46</td>
<td>74.7</td>
<td>442.4</td>
<td>-23.68</td>
</tr>
<tr>
<td>ILTJ131508.97+455843.4</td>
<td>203.6</td>
<td>0.46</td>
<td>78.9</td>
<td>466.7</td>
<td>-24.54</td>
</tr>
<tr>
<td>ILTJ134838.21+470753.9</td>
<td>123.5</td>
<td>0.51</td>
<td>137.0</td>
<td>853.9</td>
<td>-24.04</td>
</tr>
<tr>
<td>ILTJ142420.98+455845.4</td>
<td>143.2</td>
<td>0.29</td>
<td>74.4</td>
<td>329.5</td>
<td>-21.91</td>
</tr>
<tr>
<td>ILTJ145352.84+500404.6</td>
<td>1974.7</td>
<td>0.39</td>
<td>97.0</td>
<td>517.6</td>
<td>-24.32</td>
</tr>
<tr>
<td>ILTJ151829.41+515753.5</td>
<td>155.5</td>
<td>0.71</td>
<td>130.3</td>
<td>948.8</td>
<td>-24.56</td>
</tr>
<tr>
<td><strong>MEDIAN</strong></td>
<td><strong>179.6</strong></td>
<td><strong>0.46</strong></td>
<td><strong>95.5</strong></td>
<td><strong>587.2</strong></td>
<td><strong>-23.97</strong></td>
</tr>
</tbody>
</table>
Figure 5-2 – The FRII-high images from LoTSS and FIRST. The figure is split into two columns: the left image is the LoTSS 150 MHz, 6 arcsec image and the right image is the FIRST 1.4 GHz, 5 arcsec image. The corresponding source names for LoTSS and FIRST are given under each image.

Table 5-4 – The median values of the properties of the FRII-high and -lows. These values are taken from the final row in Table 5-1 and Table 5-3.

<table>
<thead>
<tr>
<th>Property</th>
<th>FRII-LOWS</th>
<th>FRII-HIGHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUMINOSITY ( \times 10^{24} \text{ W Hz}^{-1} )</td>
<td>5.8</td>
<td>179.6</td>
</tr>
<tr>
<td>REDSHIFT</td>
<td>0.17</td>
<td>0.49</td>
</tr>
<tr>
<td>ANGULAR SIZE (arcsec)</td>
<td>84.9</td>
<td>95.5</td>
</tr>
<tr>
<td>LINEAR SIZE (kpc)</td>
<td>311.9</td>
<td>587.2</td>
</tr>
<tr>
<td>MAGNITUDE</td>
<td>-23.26</td>
<td>-23.97</td>
</tr>
</tbody>
</table>

Included in the last rows of Table 5-1 and Table 5-3 are the median values of each property. A quick comparison of these demonstrates the expected difference in luminosity between the FRII-lows \( 5.8 \times 10^{24} \text{ W Hz}^{-1} \) and the FRII-highs \( 179.6 \times 10^{24} \text{ W Hz}^{-1} \), and that there is only a comparatively small difference in the host galaxy magnitudes. The FRII-highs have brighter host galaxies with a median magnitude of -23.97 compared to -23.26 for the FRII-lows. The FRII-lows are smaller in size, with an average angular size of 84.9 arcsecs and linear size of 311.9 kpc, compared to the FRII-highs at 95.5 arcsecs and 587.2 kpc. The FRII-lows cover a lower redshift range with an average redshift of 0.17. Although the LOFAR data spans a wide luminosity range at low
to medium redshifts, on average low luminosity sources will have lower redshift than higher luminosity ones. Hence, the FRII-highs have an average redshift of 0.49. These averages are summarised in Table 5-4.

5.3.3 **Comparison to whole population**

As discussed in Section 5.2 the sample of 19 FRII-lows was chosen to be representative of the population below $10^{25}$ W Hz$^{-1}$ to the extent possible with the VLA. However, the FRII-highs were chosen at random, therefore it is important to check that they are also representative of their population.

![Figure 5-3](image.png)

Figure 5-3 – The $K_s$ magnitude vs 150 MHz luminosity for both samples compared to the full Mingo et al. (2019) populations. The two sample sets are marked using plus symbols against the fainter full populations. The FRII-highs are red over yellow, and the FRII-lows are purple on blue.
In Figure 5-3 the host galaxy rest frame $K_s$-band magnitudes (Duncan et al. 2019) have been plotted against luminosity (Mingo et al. 2019). Here the full samples of LoMorph FRII-lows and -highs are marked with fainter circles in blue and yellow, respectively, with their samples overlaid with plus (+) symbols in red for the FRII-highs and purple for the FRII-lows.

Figure 5-4 contains four pairs of plots comparing properties of the sample sets with the Mingo et al. (2019) parent populations, taking a matched luminosity range between $2 \times 10^{23} - 2 \times 10^{25}$ for the FRII-lows. In these plots the colours are the same as in Figure 5-3. In the top graph luminosity is plotted, followed by $M_{K_s}$, in the third pair of graphs the distribution of sizes in kpc is given, and in the bottom plots the spread of redshifts. The differences between FRII-lows and -highs for the parent samples is discussed by Mingo et al. (2019).

From Figure 5-4 the plots indicate that the FRII-highs are well matched to the full population from Mingo et al. (2019) for all four properties. The FRII-lows have been matched for a suitable luminosity range between $2 \times 10^{23} - 2 \times 10^{25}$, and the graphs indicate that they are well matched for everything except redshift.
Figure 5-4 – Four pairs of plots to compare properties of the FRII-low and FRII-high subsamples used in this work with their parent populations from Mingo et al. (2019). (a) Compares the luminosities, (b) compares the $K_s$ magnitudes of the samples to the populations, (c) compares the size of the sources, and (d) compares the redshifts. In all four pairs of plots the left-hand side shows the FRII-lows with the sample in purple and the full population in blue, and the right hand-side shows the FRII-highs with the sample in red and the full population in yellow.
I carried out a Kolmogorov-Smirnov (KS) test to compare the subsamples with their parent populations for each property in Figure 5-4 with the null hypothesis “The FRII-highs/lows sample and respective Mingo et al. (2019) sample came from the same parent population”. For each feature the FRII-highs obtained p-values substantially higher than the required p = 0.05, allowing me to accept the null hypothesis with 95% confidence (see Table 5-5). The FRII-lows had p-values less than p = 0.05 for magnitude and redshift leading me to reject the null hypothesis for them (see Table 5-5), even though the distribution of the magnitudes is very similar. The slight difference in the magnitudes is explained by the sources being at a closer redshift. They are more intrinsically faint, and brighter things are rarer in the local Universe.

Table 5-5 – The mean, median and p-value for each of the features in the FRII-high and low samples and Mingo et al. (2019) populations. In each table the luminosity (given in units of × 10^{24} W Hz^{-1} for comparison), magnitude, length (linear size in kpc), and redshift are given with their corresponding p-values from a 2-sample KS test. table (a) contains the FRII-highs, and table (b) contains the FRII-lows. In table (b) there are additional columns for the filtered FRII-low sample and corresponding p-values, as discussed in Section 5.3.3.

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>FRII-high Sample</th>
<th>FRII-highs Mingo+ (2019)</th>
<th>P-VALUE</th>
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</thead>
<tbody>
<tr>
<td>LUMINOSITY (\times 10^{24} \text{ W Hz}^{-1})</td>
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<td>454.1</td>
<td>301.5</td>
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<tr>
<td>MAGNITUDE</td>
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<td>-23.86</td>
<td>-24.14</td>
</tr>
<tr>
<td>LENGTH (kpc)</td>
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<td>629.1</td>
<td>531.7</td>
</tr>
<tr>
<td>REDSHIFT</td>
<td>0.49</td>
<td>0.48</td>
<td>0.57</td>
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</table>

(a)

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>FRII-low Sample</th>
<th>FRII-lows Mingo+ (2019)</th>
<th>P-VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUMINOSITY (\times 10^{24} \text{ W Hz}^{-1})</td>
<td>5.8</td>
<td>6.8</td>
<td>6.3</td>
</tr>
<tr>
<td>MAGNITUDE</td>
<td>-23.26</td>
<td>-23.06</td>
<td>-23.63</td>
</tr>
<tr>
<td>LENGTH (kpc)</td>
<td>311.9</td>
<td>281.2</td>
<td>300.1</td>
</tr>
<tr>
<td>REDSHIFT</td>
<td>0.17</td>
<td>0.20</td>
<td>0.38</td>
</tr>
</tbody>
</table>

(b)
5.4 RESULTS

Having ensured that both the FRII-low and FRII-high samples should be reasonably representative of the catalogued properties of their parent populations for the luminosity range, and generated images of each sample at each frequency, I can begin to investigate the properties of the groups.

The aim of this research is to investigate whether there are any significant differences in the source physics between the two luminosity populations of FRIIs. To do this I investigated the morphology of the FRII-lows and -highs to ascertain if the FRII-lows have the same compact morphology (i.e., occurrence of hotspots) as the more luminous FRII-highs. This is covered in Section 5.4.1.

In Section 5.4.2 I have calculated the integrated spectral indices of the FRII-lows sample, including those of the cores and lobes. These are used later to explore the possibility of the remnant and restarting sources.

Section 5.4.3 describes my investigation into the hypothesis that those sources in the sample that are most similar to FRII-highs in host galaxy magnitude and radio luminosity, will also have similar source dynamics. Here I divide the sample into small sub-groups and explore the compact features within each group.

One possible explanation for the origin of FRIIs with low luminosity is that they may be older sources, fading but still maintaining some of their FRII morphology (Mingo et al. 2019). If this is the case, then their total integrated spectral index (see Section 1.1) may be steeper. These sources may also satisfy other criteria for being a remnant or restarting candidate (see Section 1.6) where their activity may have completely switched off or become negligible. Sections 5.4.1.3 and 5.4.4 cover my research into these two areas.
5.4.1 MORPHOLOGY

The aim of this section is to compare the prevalence of compact features in the FRII-low sample and investigate other signs of current jet behaviour.

5.4.1.1 Defining compact features

To investigate the source dynamics of the FRII-lows and see how they compare to those of the FRII-highs, the compact features in the VLA images for the FRII-lows were compared to those in the FIRST images for the FRII-highs. To do this I have used a similar definition to Mullin et al. (2008) to classify compact features in the sources. They describe hotspots as features which are not part of a jet, are smaller than 10% of the main axis length of the source and have a peak brightness over ten times the off-source noise. Their sample was a set of much more luminous FRII sources. I have chosen to use the ten sigma contours defined in CASA to determine bright regions. This was decided after a series of tests with various multiples of the RMS noise on a couple of sources, one with a clear circular core and the other with obvious hotspot features. The VLA contours are given in Figure 5-5 and the FIRST contours in Figure 5-6. I have then used DS9 to measure the size of these regions along the axis of the source, and the length of the source itself. Due to these measurements being only accurate to a single pixel in length the uncertainties will be $\sim \pm 0.3$ arcsec. These calculations are given in Table 5-6 and Table 5-7 for the VLA and FIRST sources respectively.

If the feature is less than 10% of the length of the source than it has been considered a compact feature. If this compact feature is $> 50\%$ away from the centre of the source, then it is classified as a hotspot. If it is centrally located, it is classified as a core feature. Those with core features are discussed further in Section 5.4.4 in reference to remnant and restarting sources.

5.4.1.2 Locating compact features

The compact features, as defined in the previous section, have been identified in both the VLA images of the FRII-lows and the FIRST images of the FRII-highs. The ten sigma contours for the FRII-low VLA images are shown in Figure 5-5. Twelve out of thirteen VLA-detected sources included regions over ten times the
RMS in brightness. The calculated RMS is that given in Table 5-2 for the full 33 arcminute image. The sizes of the contours have been measured using DS9 along the major axis of the jet and are given in Table 5-6. All these measurements are given in arcseconds. Table 5-6 summarises whether these compact features can then be classified as hotspots, cores, or possible jet features.

The possible jet features have occurred in two of the brighter sources. Mullin et al. (2008) define a jet as at least 4 times as long as it is wide, and as a narrow ridge running through more diffuse emission, or a narrow feature in the inner part entering more extended emission in the outer part. Both the northern lobe of ILTJ115011.27 and the western lobe of ILTJ150827.77 could potentially have jets. For ILTJ150827.77 its length is four times its average width, though ILTJ115011.27’s ten sigma contours widen out. ILTJ115011.27 is a high dynamic range source, causing the 10 sigma contours to not fully capture the features of the source. Visually there is a compact core and at least a hotspot feature in the northern lobe, and possibly the southern lobe. The core integrated spectral index has been calculated later and used further in Section 5.4.4. These compact features have been marked with a bracket in Table 5-6, but not included in the total.

Two other sources of interest are ILTJ113626.52 and ILTJ133729.25, as they have two distinct regions at their core. Table 5-6 includes not only the size of the individual core components but the full length across both the components. These are marked with an * in Table 5-6. For both sources the full size of both core components is \( \lesssim 6 \) arcseconds and would not have been detected with the LoTSS resolution.

ILTJ133217.44 appears to have two hotspots in each lobe (see Section 1.2). ILTJ121623.58 and ILTJ144650.49 have very small hotspots that may be patches of brightness in a fairly uniform lobe. However, they are both centrally located, and their size is not unusually small compared to the other sources, so they have been included as hotspots.

Figure 5-6 and Table 5-7 provides the same information for the FIRST images of the FRII-highs. Here six out of the ten sources have detections over ten times the image RMS. Possibly due to a higher SNR and a lower resolution in the FIRST images, some of the regions are larger than 10% of the source size. Therefore, although by-eye the sources are clearly edge-brightened they are not small enough to be compact by the definition used here.
Figure 5-5 – The VLA images of the FRII-low sample with 10 sigma contours. These are the twelve sources which have detections over ten times their rms level. In order from top to bottom, left to right: ILTJ112654.44, ILTJ113626.52, ILTJ115011.27, ILTJ121623.58, ILTJ130605.63, ILTJ133217.44, ILTJ133729.25, ILTJ135152.95, ILTJ135630.51, ILTJ144650.49, ILTJ145759.29, ILTJ150827.77. These contours have been used to determine whether the sources contain hotspots, cores, or jets as described in the text.
Table 5-6 – A summary of the occurrence of compact features in the VLA images of the FRII-lows. The second and third columns give the average lengths in arcseconds, of the source in the image and the ten sigma regions present. All uncertainties are $\approx 0.3$ arcsec as described in Section 5.4.1.1. The final three columns indicate whether these regions represent a hotspot, core, or possible jet. The final row gives the percentage of each feature. The features marked with () and the two sources marked with an * are described in detail in Section 5.4.1.2. The uncertainties of the percentages are calculated as described in the text.

<table>
<thead>
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<th>SOURCE</th>
<th>LENGTH AVERAGE</th>
<th>REGION AVERAGE</th>
<th>CORES</th>
<th>HOT-SPOTS</th>
<th>JETS</th>
</tr>
</thead>
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<td>3.5</td>
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<td>-</td>
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<td>ILTJ113626.52</td>
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<td></td>
<td></td>
<td>1.1</td>
<td>C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
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<td>C*</td>
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<td>1.9</td>
<td>C</td>
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<td>17.0</td>
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<td>J</td>
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<td>$26.3^{+22.8}_{-14.9}$</td>
<td>$10.5^{+22.1}_{-8.8}$</td>
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</table>
Figure 5-6 – The FIRST images of the FRII-high sample with 10 sigma contours. These are the six sources which have detections over ten times their rms level. In order from top to bottom, left to right: J104706, J114559, J121849, J131508, J134837, J142420. These contours have been used to determine if the sources contain hotspots, cores, or jets as described in the text.
Table 5-7 – A summary of the occurrence of compact features in the FIRST images of the FRII-highs. The second and third columns give the average lengths of the source in the image and the ten sigma regions present. All uncertainties are $\pm 0.3$ arcsec as described in Section 5.4.1.1. As described in the text, the criteria has been relaxed to 20% and includes the sources marked with (HS). The final three columns indicate whether these regions represent a hotspot, core, or possible jet. The final row gives the percentage of each feature. The uncertainties of the percentages are calculated as described in the text.

<table>
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<tr>
<th>SOURCE</th>
<th>LENGTH AVERAGE</th>
<th>REGION AVERAGE</th>
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<th>HOT-SPOTS</th>
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</tbody>
</table>

| PERCENTAGE OF SAMPLE | 0.0 $^{+32.1}_{-80.0}$ | 30.0 $^{+30.8}_{-19.7}$ | 0.0 $^{+32.1}_{-60.0}$ |
5.4.1.3 Comparison of compact features

The final rows in Table 5-6 and Table 5-7 give the percentage of each compact feature within the images that have useful detections. The errors on the percentages are calculated using the Agresti-Coull method using a 95% confidence interval. Both of the samples are small in size, leading to large uncertainties on the percentages. In the FRII-lows there was only one source with no detected compact features giving a detection rate of $92.3^{+7.7}_{-27.7}$ %. For the FRII-highs, three have detected compact features, giving a detection rate of $30.0^{+30.8}_{-19.7}$ %. The FIRST resolution is not sufficient to apply the 10% of source length criterion for a significant fraction of the FRII-highs, and so to ensure that the hotspot definition can be applied to all of the FIRST sample, I have relaxed this criterion to 20%. The features meeting the relaxed criterion are marked with () in Table 5-7, and giving $60.0^{+23.3}_{-21.8}$ % of the sample containing compact features. However, it’s important to note that all of the compact features, including hotspots, identified in the higher-resolution VLA FRII-low sample also meet the original 10% criterion of Mullin et al. (2008). Mullin et al. (2008) also note that a lower resolution leads to a larger hotspot size, and only one of their 98 3CRR FRIIs lacked any hotspot features. Comparing the FRII-lows and -highs shows that compact features are very common in the FRII-lows, and that hotspots are less prevalent in the FRII-lows than the FRII-highs.

The FRII-lows show a high prevalence of compact core features. These features were less distinct in the original LoTSS images due to the lower resolution (and frequency), or partially obscured due to nearby extended emission and lower resolution. However, in the VLA images a mix of core features are presented, including double cores and compact, circular cores. These cores are present in $47.4^{+20.9}_{-20.9}$ % of the images with detections. In the FRII-highs there are no sources that have FIRST-detected cores. This could be caused by sample selection and the uncertainty for this is given. Even considering this, the FRII-lows show a higher prevalence of cores over the FRII-highs. ILTJ1150011.27 has not had a core defined using the definition given in Section 5.4.1.1 as it is too bright. However, by eye it has a compact core component. This has not been included in the comparison and does not affect the conclusions about core prevalence, but it is used later in Section 5.4.4 when looking at remnants and restarters.
Both the FRII-lows and -highs have hotspots. The FRII-lows have 26.3 $^{+22.8}_{-14.9}$ % of sources with hotspots. As discussed in the previous section there are two sources where the hotspots may be small, bright areas within a fairly uniform lobe. This may decrease the number of hotspots present in the sample. The FRII-highs have 60.0 $^{+23.3}_{-26.8}$ % of the sample with hotspots, demonstrating a higher prevalence for hotspots in the higher luminosity sources.

As previously mentioned, two sources or 10.5 $^{+22.1}_{-8.8}$ % in the FRII-lows have the possibility of jet features. There are none in the FRII-high sample. Again, like the cores, this could be caused by sample selection. However, these two sources could also be an example of how the morphological classification of a source can change at different frequencies. Having a brighter central region, and in the case of ILTJ150827.77 a clear variation between lobes, would change their classification from FRII to hybrid or an FRI source (see Section 1.4).

The combination of the images from Figure 5-5 and Figure 5-6, and Table 5-6 and Table 5-7 show a variation in morphology between FRII-lows and FRII-highs. In the two samples the FRII-lows have presented with a higher variety and percentage of compact features. The key differences between the two populations found in my investigation are:

(i) 47.4 $^{+20.0}_{-20.0}$ % of the FRII-lows have cores, while the FRII-highs have no sources demonstrating a bright central region

(ii) The FRII-lows have 26.3 $^{+22.8}_{-14.9}$ % of the sample with hotspots, whilst the FRII-highs have 60.0 $^{+23.3}_{-26.8}$ % demonstrating a higher prevalence for hotspots

(iii) Jet features may be present in 10.5 $^{+22.1}_{-8.8}$ % of the FRII-lows. These sources may be examples of how classification can change at different frequencies

(iv) There are two sources in the FRII-lows with clear double core features, which will be discussed further in Section 5.4.4 and Chapter 6.
I made a direct comparison between the FIRST maps and the VLA maps tapered to the LoTSS resolution to compare compact features. However, because the FRII-lows typically have a much lower total flux than the FRII-high sample the dynamic range was reduced such that only 3 images satisfy the Mullin et al. (2008) ten sigma criterion. Therefore, a fair comparison at this resolution is not possible because of the difference in typical total flux and surface brightness of the two samples. A by-eye check shows the possibility of six sources with core features and two with hotspots in the tapered VLA images. As the FRII-highs demonstrate obvious hotspots and no cores at a similar resolution this confirms the high prevalence of cores in the FRII-lows and hotspots in the FRII-highs.

### 5.4.2 Spectral Indices

Spectral analysis is useful for distinguishing between active and remnant sources where the jet has turned off (See Section 1.6). I chose to compare the sample of FRII-lows to typical active radio galaxies by calculating their integrated spectral indices ($\alpha$, where radio flux density $S_\nu \propto \nu^{-\alpha}$) (see Section 1.3). Mingo et al. (2019) demonstrated that over half of their FRII-lows have integrated spectral indices from LoTSS to NVSS between $\sim$0.7 and 1. I generated regions for each source based on the $3\sigma$ contours on the LoTSS images. Using these regions, I then used the RADIOFLUX tool\(^39\) to calculate the total flux on the VLA images tapered to the LoTSS 6 arcsec resolution. These values were checked against CASAs imfit procedure and the results match within error values. $\alpha_{1500}^{150}$ was calculated for the sample using the total flux densities from LoTSS and the VLA and the results are given in Table 5-8.

The uncertainties on the integrated spectral indices are calculated using the following formula (e.g., Jurlin et al. 2020):

$$\alpha_{err} = \frac{1}{\ln\left(\frac{\nu_2}{\nu_1}\right)} \sqrt{\left(\frac{S_{1,err}}{S_1}\right)^2 + \left(\frac{S_{2,err}}{S_2}\right)^2}, \quad \text{Eq. 5-2}$$

where $S_1$ and $S_2$ are the flux densities at frequencies $\nu_1$ and $\nu_2$ respectively, and $S_{1,err}$ and $S_{2,err}$ are the respective flux calibration uncertainties. These variations are $\sim$5% for the VLA L-band\(^40\) and $\sim$20% for LoTSS (Shimwell et al. 2019). As

\(^39\)https://www.github.com/mhardcastle/radioflux  
\(^40\)https://science.nrao.edu/facilities/vla/docs/manuals/oss2019A/performance/fdscale
these values are constant this gives an uncertainty value of $\pm 0.1$ for all of these integrated spectral indices.

Of the 19 sources, six images had non-detections or very faint detections from the VLA observations. Therefore, when calculating $\alpha_{1500}$ using the total flux density within the LoTSS $3\sigma$ contours overlaid on these images, the value can only be a lower limit (these are indicated in Table 5-8). I calculated an upper limit on the 1.5 GHz flux based on the $3 \times$ RMS level within the source region. Including it in the spectral index formula gives me a lower limit on the value of alpha.

The remaining sources have integrated spectral indices that lie in the range of $\sim 0.5$ to 1.0 which is typical for active radio galaxies. As per Mingo et al. (2019)’s findings using NVSS, seven of these sources (about half of the sample) have an $\alpha$ value in the range of 0.7 to 1.0, matching the typical values expected for FRII-higns.

Table 5-8 also gives the $\alpha_{1500}$ for the cores and lobes of the 10 sources where core features were present in the VLA. To calculate these a 6 arcsec region was inscribed over the core in the VLA image to represent a matching beam resolution of LOFAR. The total flux was calculated, as before using RADIOFLUX including a background subtraction, for both the VLA and LoTSS images and used to determine the integrated spectral index of the core. It should also be noted that because of the beam size and low resolution in the LOFAR images, contamination from extended source flux may affect the integrated spectral indices.

As seen in Table 5-6, ILTJ113626.52 and ILTJ133729.25 have two core components. For ILTJ113626.52 the total size of both these components fits within a 6 arcsec region. ILTJ133729.25 has a total core size just larger than the LOFAR 6 arcsec beam size, so when the region is placed the edges of the bright core spots are not within the area. This will have some effect on the outcome of the core’s integrated spectral index.
Table 5.8 – The integrated spectral indices of the sample of FRII-lows. The second column gives the integrated spectral index from LoTSS to the VLA, calculated as described in Section 5.4.1.3. The third and fourth columns contain the same integrated spectral index for the core and the lobes (where applicable). * ILTJ115011.27 was defined as having a jet like structure starting at the centre, as described in the text. The uncertainty for all these results is ± 0.09 and the description for all of these calculations is contained in the text of Section 5.4.1.3.

<table>
<thead>
<tr>
<th>SOURCE NAME</th>
<th>$\alpha_{1500 \text{ MHz}}^{150 \text{ MHz}}$</th>
<th>$\alpha_{1500 \text{ MHz}}^{150 \text{ MHz}}$ CORE</th>
<th>$\alpha_{1500 \text{ MHz}}^{150 \text{ MHz}}$ LOBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILTJ105946.75</td>
<td>&gt; 1.45</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ILTJ112015.05</td>
<td>&gt; 1.17</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ILTJ112654.44</td>
<td>0.49</td>
<td>0.14</td>
<td>0.53</td>
</tr>
<tr>
<td>ILTJ113626.52</td>
<td>0.59</td>
<td>0.52</td>
<td>0.59</td>
</tr>
<tr>
<td>ILTJ114351.49</td>
<td>&gt; 1.13</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ILTJ115011.27</td>
<td>0.50</td>
<td>0.32*</td>
<td>0.51*</td>
</tr>
<tr>
<td>ILTJ121623.58</td>
<td>0.67</td>
<td>-0.17</td>
<td>0.71</td>
</tr>
<tr>
<td>ILTJ130109.83</td>
<td>0.71</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ILTJ130605.63</td>
<td>0.97</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ILTJ133217.44</td>
<td>0.97</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ILTJ133729.25</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>ILTJ134315.98</td>
<td>&gt; 1.27</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ILTJ135152.95</td>
<td>0.64</td>
<td>0.23</td>
<td>0.66</td>
</tr>
<tr>
<td>ILTJ135630.51</td>
<td>0.69</td>
<td>0.23</td>
<td>0.72</td>
</tr>
<tr>
<td>ILTJ144464.12</td>
<td>&gt; 1.14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ILTJ144650.49</td>
<td>0.65</td>
<td>0.41</td>
<td>0.67</td>
</tr>
<tr>
<td>ILTJ145759.29</td>
<td>0.68</td>
<td>0.13</td>
<td>0.71</td>
</tr>
<tr>
<td>ILTJ145936.33</td>
<td>&gt; 1.25</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ILTJ150827.77</td>
<td>0.54</td>
<td>0.10</td>
<td>0.57</td>
</tr>
</tbody>
</table>
The core integrated spectral indices divide into two different groups. There are four sources (ILTJ113626.52, ILTJ115011.27, ILTJ133729.25 and ILTJ144650.49) that have comparatively high values for $\alpha_{\text{core}}$. They have values ranging from 0.32 to 0.58. Morphologically three of these sources contain the two with a double core and the one with an extended core that could be a possible restarting source (see Section 1.6). ILTJ115011.27, at 0.32 is the high dynamic range source. This source was not defined as having a core, but it was bright enough in the central region to produce an elongated structure that may be a jet. However, I have chosen to calculate a possible core as part of this feature. The elongated bright region will have affected its value for $\alpha_{\text{core}}$. The remaining sources have lower positive values and a negative value for $\alpha_{\text{core}}$, of -0.17 and between 0.1 to 0.23. These sources are all those with bright circular cores.

The lobe flux was calculated by subtracting the flux in the 6 arcsec region away from the total flux within the $3\sigma$ contour region. For each of the sources there is a small difference between the integrated spectral index of the whole source and that of the lobes. The lobes are slightly steeper, and there is little indication that the cores are having a disproportionate effect (as the combined spectral index is an average of the two values).

5.4.3 Magnitude and Luminosity Groupings

Figure 5-7 shows the same quantities as Figure 5-3, $K_s$ magnitude versus radio luminosity ($L_{150}$ W Hz$^{-1}$), however the sample set of 19 FRII-lows has now been divided into three groups according to their host galaxy magnitude and radio luminosity. On plotting the sample set in relation to their parent population and the FRII-highs it became clear that the sample could be clustered into different regions of parameter space.
The three sub-groups based on magnitude and luminosity. The plot is the same as Figure 5-3 with the inclusion the locations of the three sub-groups within the FRII-low sample set. These groups have been coloured such that Group 1 is yellow, Group 2 is cyan, Group 3 is purple.

Group 1 can be distinguished by containing five sources that are very clearly of a lower host galaxy magnitude than the rest of the sample, and two sources whose host galaxy magnitudes are closer to the minimum of the remainder of the sample but in conjunction with their radio luminosities they lie outside the main clustering of the sample. Group 2 contains a small cluster of mid-value host galaxy magnitude and radio luminosity sources that form a small group midway between Group 1’s outliers and Group 3. Group 3 is the largest group and a cluster of sources that sits squarely in the parent population of sources and directly under the greatest concentration of FRII-highs, giving them host galaxies with similar absolute magnitudes to the FRII-highs. This sub-group contains the brightest sources with the most comparable host galaxies to the FRII-high population. It is with these sub-groups I can investigate whether, in a situation where host galaxy is influencing morphology, low-luminosity sources with the same host properties as the high luminosity sources, will have a higher prevalence of hotspots.
Any grouping of this sort is somewhat arbitrary, but it is a useful tool to explore the dependence of compact features on host properties and radio luminosity (which is a proxy for jet power). To check whether the choice of grouping influenced the conclusions I have also split the sample based on magnitude alone. Here it would divide along a line at $M_{k_s} = -23.0$ as this represents the limit of the FRII-high population, dividing the FRII-low sample into two subgroups. Magnitude has also been used to divide the sample into three subgroups. Here Group 3 would remain the same, Group 2 would gain the two closest members of Group 1, and the five most outlying sources would remain in Group 1. As a comparison, the prevalence of compact features in these groups is discussed later.

5.4.3.1 Comparisons

The intention with splitting the sample set into the three subgroups was to explore the spread of compact features between the different subgroups. The simplest comparison to see if Group 3 shares source dynamics with the FRII-highs, is to split the images into the three subgroups and investigate if there are any obvious morphological differences between the three groups. Figure 5-8 shows thumbnails of the source images with the contours for the compact features have been divided into the subgroups. All 19 of the images have been included to demonstrate the number of sources with compact features, number of detections, and number of non-detections within each subgroup. These percentages are then given in Table 5-9 along with Agresti-Coull 95% confidence intervals. The percentages are also calculated for the subgroups based on host galaxy magnitude only divisions, as discussed earlier.
Group 2

(b)
Figure 5-8 - Thumbnails of the LoTSS and VLA images divided into the three sub-groups, with the contours for the compact features overlaid. The individual groups and how they are selected are described in detail in Section 5.4.3.
Table 5-9 – The percentage prevalence of compact features and non-detections in the sub-groups of the FRII-low sample. The top table shows the three sub-groups described in the text and shown in Figure 5-7. The middle and bottom tables show the percentage prevalence for the sub-groups as divided by magnitude only, described in the text. The error bars are calculated to the 95% confidence with the Agresti-Coull method.

Magnitude and luminosity sub-groups

<table>
<thead>
<tr>
<th>Sub-group 1</th>
<th>Sub-group 2</th>
<th>Sub-group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COMPACT FEATURES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6/7</td>
<td>2/4</td>
<td>4/8</td>
</tr>
<tr>
<td>(86 ( \pm \frac{1.8}{1} ) %)</td>
<td>(50 ( \pm \frac{3.5}{1} ) %)</td>
<td>(50 ( \pm \frac{2.9}{1} ) %)</td>
</tr>
</tbody>
</table>

Magnitude sub-groups (three)

<table>
<thead>
<tr>
<th>Sub-group 1</th>
<th>Sub-group 2</th>
<th>Sub-group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COMPACT FEATURES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/5</td>
<td>4/6</td>
<td>4/8</td>
</tr>
<tr>
<td>(80 ( \pm \frac{1.8}{2} ) %)</td>
<td>(67 ( \pm \frac{3.7}{2} ) %)</td>
<td>(50 ( \pm \frac{2.9}{1} ) %)</td>
</tr>
</tbody>
</table>

Magnitude sub-groups (two)

<table>
<thead>
<tr>
<th>Sub-group 1</th>
<th>Sub-group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COMPACT FEATURES</strong></td>
<td></td>
</tr>
<tr>
<td>5/6</td>
<td>7/13</td>
</tr>
<tr>
<td>(83 ( \pm \frac{1.5}{2} ) %)</td>
<td>(54 ( \pm \frac{3.3}{2} ) %)</td>
</tr>
</tbody>
</table>

Combining the information in Table 5-9, and Figure 5-8, almost all of Group 1 shows a compact feature, defined previously (see Section 5.4.1). In each of Groups 2 and 3 about half the sources have compact features. They also have a higher fraction of non-detections. These trends of a higher prevalence of compact features in Group 1 and non-detections in Groups 2 and 3 remains, even when the sample is divided into two or three sub-groups based on host galaxy magnitude only. It is, however, important to note that with such small samples the uncertainties are large, and the proportions of compact features are consistent within the uncertainties.
Figure 5-9 – A comparison of properties of the three sub-groups. In each graph the parent population of the FRII-highs are the faded grey filled bars, and the sub-groups 1, 2 and 3 are the bold lines, coloured yellow, cyan and purple (dashed), respectively. (a) shows a comparison of the different sizes in kpc, (b) the different fluxes in mJy, and (c) the redshifts.
Figure 5-9 presents a comparison of properties for the different sub-groups and the FRII-highs from Mingo et al. (2019). In Figure 5-9 (a) and (b) the size (kpc) and total flux (mJy) (respectively, as calculated by Mingo et al. (2019)) are investigated, and in (c) the redshifts (where \( z \leq 0.8 \) for the data set). It is clear there are obvious differences between the three sub-groups, where Group 2 overlaps with some of the highest values in Group 1 and lowest values in Group 3 for each property.

From Figure 5-9 the majority of Group 1 comprises the smallest sizes, lowest fluxes, and lowest redshifts. Group 3 contains a higher number of larger sources; however, they also have lower fluxes and higher redshifts. In comparison to the FRII-high parent population, Group 3 more closely matches for size. The total fluxes for the sub-groups, although lower than the FRII-highs, shows no significant difference between the sub-groups. This is to be expected as the sources had to meet a flux requirement for detection by the VLA. These conclusions were confirmed through 95% confidence KS tests as in Section 5.3.3.

### 5.4.3.2 Conclusions

The aim of this section was to investigate the possibility the sub-group of the FRII-low sample that most closely reflects that of the FRII-highs in host galaxy magnitude, also has similar source dynamics to the FRII-highs.

There is a higher prevalence of compact features in Group 1 than Group 3. This fraction does not significantly change when the sub-groups are considered just on a host galaxy magnitude split, into two or three sub-groups. Group 1 contains the majority of hotspot features, and those that are in Group 3 are the ones which are fluctuations in the uniform lobes (see Section 5.4.1.2), whereas Group 3’s compact features are mainly cores. As Group 1 contains the lowest radio luminosity sources (a proxy for jet power) this could imply that these are low powered jets in a weaker environment. Group 3 contains larger sources with higher redshifts, and lower fluxes, which could explain the lower number of compact features detected in the VLA images. As previously noted, the sample sizes are small, and the uncertainties are large meaning the proportion of compact features are consistent within the uncertainties.
5.4.4 REMNANTS AND RESTARTING SOURCES

Mingo et al. (2019) suggest a possible explanation for the origin of some of the FRII-lows is that they can be attributed to an older, fading population i.e., they are in the remnant or restarting phase of their life cycle (see Section 1.6). During this period the typical indicators of active radio galaxies, such as cores, jets and hotspots are expected to have disappeared or to be highly diminished, and the expanding and ageing emission in the extended lobes will cause them to dissipate and fade. It can be hard to identify whether a source should be considered a remnant radio galaxy candidate. Initially individual cases were studied (e.g., Cordey 1987; Brienza et al. 2016; Randriamanakoto et al. 2020) or samples of candidates selected on a single criterion (e.g., Parma et al. 2007; Saripalli et al. 2012). As my sample is from LoTSS I have chosen to investigate their remnant nature using a method similar to that in Jurlin et al. (2021), whose criteria are based on a culmination of studies by Parma et al. (2010), Saripalli et al. (2012), Hardcastle et al. (2016, 2018a), Brienza et al. (2017), Godfrey et al. (2017), Mahatma et al. (2018), Jurlin et al. (2020), and Shabala et al. (2020), and is complementary to the work found in Morganti et al. (2021a, 2021b).

There are four criteria that these studies focus on when determining the possibility that a source is granted remnant candidate status. These criteria are listed below and explained in detail in the following sections:

(i) Ultra-steep integrated spectral index
(ii) Spectral curvature criterion $\geq 0.5$
(iii) Lower than expected core prominence for active radio galaxies
(iv) Morphology
5.4.4.1  Ultra-steep spectral indices

Ultra-steep spectrum (USS) sources are defined as having indices steeper than ~1.2 (Komissarov & Gubanov 1994). There is no replenishment of new electrons, and the spectrum reflects the losses from radiation and expansion. It is common to see a steeper spectrum above 1.5 GHz due to the higher radiative loss of higher energy electrons, but when it is also present at the lowest frequencies it is a sign of the oldest sources. Therefore, a presence of a steeper spectrum at lower frequencies indicates an aged source. As such an USS is often the criterion by which a remnant candidate is chosen.

To explore the possibility of a significant spectral curvature across different frequencies, a set of images at a different, higher frequency was required. Here I made use of the VLA Sky Survey (VLASS) quick look images obtained from http://cutouts.cirada.ca/. VLASS is a 2 – 4 GHz VLA survey with a resolution of ~2.5 arcsec, and all the images were taken from VLASS Epoch 2. The quick look images have some limitations in their accuracy compared to the higher quality single epoch images, however the single epoch images are not yet released and do not cover the full survey. These limitations are mainly due to dynamic range (within a few beams of a bright source) and, because they are not self-calibrated, effects on the peak flux densities. This may impact the total integrated spectral index for extended sources. In comparison the flux density calibration (the error for both is ~3%)41, positional accuracy (manually checked for all 19 sources), and noise for the quick look images are all comparable to the single-epoch (science-ready) ones. The more accurate single-epoch images will become available in the future43.

Table 5-10 lists the total integrated spectral indices for the 19 sample sources from Section 5.4.1.3. If the USS criterion is taken as > 1.2 there are four sources with a value over this boundary: ILTJ105946.75, ILTJ112015.05, ILTJ134315.98 and ILTJ145936.33. If the criterion is relaxed to > 1.1 for the sources where the lower limits were calculated, as Morganti et al. (2021b), then the two remaining sources whose integrated spectral indices were calculated as lower limits are now included. These are all the sources where an upper limit on the flux had to be calculated using 3 × RMS. This gives 6 possible remnant candidates based on the USS criterion.

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41 https://science.nrao.edu/vlass/data-access/vlass-epoch-1-quick-look-users-guide
42 https://science.nrao.edu/vlass
43 https://science.nrao.edu/vlass/vlass-data/basic-data-products
Table 5-10 – A comparison of the integrated spectral indices of the sample of FRII-lows at different frequencies. The two integrated spectral index columns give α comparing between LoTSS and the VLA. In the case of the lower limits the spectral indices have been calculated as described in the text. The errors on the spectral indices are based on the survey’s flux density calibration and are uniform for each α. These are all ± 0.1 and the calculation is described in Section 5.4.1.3.

<table>
<thead>
<tr>
<th>SOURCE NAME</th>
<th>α_{150 MHz}</th>
<th>α_{150 MHz}</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILTJ105946.75</td>
<td>&gt; 1.5</td>
<td>ILTJ133729.25</td>
</tr>
<tr>
<td>ILTJ112015.05</td>
<td>&gt; 1.2</td>
<td>ILTJ134315.98</td>
</tr>
<tr>
<td>ILTJ112654.44</td>
<td>0.5</td>
<td>ILTJ135152.95</td>
</tr>
<tr>
<td>ILTJ113626.52</td>
<td>0.6</td>
<td>ILTJ135630.51</td>
</tr>
<tr>
<td>ILTJ114351.49</td>
<td>&gt; 1.1</td>
<td>ILTJ144644.12</td>
</tr>
<tr>
<td>ILTJ115011.27</td>
<td>0.5</td>
<td>ILTJ144650.49</td>
</tr>
<tr>
<td>ILTJ121623.58</td>
<td>0.7</td>
<td>ILTJ145759.29</td>
</tr>
<tr>
<td>ILTJ130109.83</td>
<td>0.7</td>
<td>ILTJ145936.33</td>
</tr>
<tr>
<td>ILTJ130605.63</td>
<td>1.0</td>
<td>ILTJ150827.77</td>
</tr>
<tr>
<td>ILTJ133217.44</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

5.4.4.2 Spectral Curvature

As more higher energy electrons will radiate away faster it would be expected that a steeper spectral index would be found at higher frequencies. The spectral curvature (SPC) criterion looks to find a significant difference between a total integrated spectral index at a higher frequency to a lower one. This would indicate a recent decrease in particle acceleration that is not yet observable at lower frequencies. In Brienza et al. (2017) SPC is defined as 0.5 ≤ α_{325}^{150} < 1, and α_{325} ≥ 1.5 (i.e. α_{325}^{1400} − α_{150}^{325} > 0.5), whereas Jurlin et al. (2021) defines SPC as α_{1400}^{6000} − α_{150}^{1400} > 0.5 in order to encompass the higher frequencies.

Using the same regions defined in Section 5.4.1.3, α_{150}^{1500} and α_{1500}^{3000} were calculated, and the definition of SPC to be α_{1500}^{3000} − α_{150}^{1500} > 0.5 to determine if any of the sources in the sample satisfy this selection criteria for being a remnant candidate. The majority of the detected VLASS images appear to be core dominated, with little to no extended emission detected. As the images have not sampled enough of the full source emission in most cases then I have
chosen to drop this criterion for remnant detection. I believe this will have little impact as in the results of Jurlin et al. (2021) none of their selected remnant candidates satisfied their SPC criteria. It is also worth noting that I have used a lower frequency range to calculate the SPC making it harder to detect curvature, than for Jurlin et al. (2021).

5.4.4.3 Core Prominence

The core prominence (CP) of an extended radio galaxy can act as an indication of how active the central region of the extended source is. If there is a core present there could be a low level of activity, or the source could be a restarter. The CP is the ratio of the higher frequency core flux to the low frequency total flux. Given this, any compact source such as CSOs and GPSs (see Section 1.5) will have high CPs. The CP can also be affected by relativistic beaming. This means it is more reliable to consider the CPs of the sample as a whole rather than looking at individual sources. Typical values can range from 0.001 to 0.1 for active radio galaxies with the most powerful ones being as low as $\sim 10^{-4}$, and the highest values $> 0.1$ being attributed to FR0s (Giovannini et al. 1988; Mullin et al. 2008; Baldi et al. 2015; Brienza et al. 2017).

I have used $CP = \frac{S_{1500\text{ core}}}{S_{150\text{ Total}}}$ for the ten sources (including ILTJ115011.27, see Section 5.4.2) where a core was detected in the VLA images. The total flux for the core and source was calculated as described in Section 5.4.2. de Ruiter et al. (1990) show that there is an inverse relationship between luminosity and CP in the B2 sample. This was adjusted by Jurlin et al. (2021) for $H_0$ when they plotted and compared their values. I have plotted this adjusted relationship and my calculated CP values for the ten sources in Figure 5-10.

It can clearly be seen that the majority of the sources lie within a reasonable scatter distance from the line. As the line is a calculated median of the previous data this is to be expected. There is one source which is a substantial distance away from this relationship, ILTJ113626.52. However, it is still within the range, [0.001, 0.1], considered to be active radio galaxies.
Figure 5-10 – The core prominences plotted against luminosity and the de Ruiter et al. (1990) relationship. The blue line is taken from Jurlin et al. (2021) and is adjusted for $H_0$.

5.4.4.4 Morphology

The traditional definition of a remnant radio galaxy is a relaxed morphology with no compact features, such as hotspots, cores, and jets (Blundell et al. 1999, Wang & Kaiser 2008). Determining a remnant radio galaxy from morphology can be complicated because of the shape of the radio galaxy during its active phase and how expansion may cause its amorphous shape to develop. The varying resolution and data quality of images also make it difficult to make clear distinctions about the morphology. However, it can be a useful criterion to determine remnant candidates (Saripalli et al. 2012). Brienza et al. (2017) consider remnant candidates to have a relaxed morphology with a low surface brightness in the low frequency images ($SB_{150 \text{ MHz}} < 50 \text{ mJy arcmin}^{-2}$), and an absence of any compact features in both their low and high frequency images.

As the SB aspect is arbitrary to choose an appropriate surface brightness threshold, Jurlin et al. (2021) opts not to use it in their selection process.

Of the 13 VLA observations that resulted in scientifically useful detections, all bar one has a compact feature such as a hotspot, core, or possible jet. The remaining one (ILTJ130109.83) does not have an amorphous structure in either the LoTSS or VLA image. In the six sources left in the sample, which were those
with the lower limit USS, there are four sources that meet the criteria of relaxed morphology and no compact features in both low and high frequencies; ILTJ105946.75, ILTJ112015.05, ILTJ134315.98 and ILTJ145936.33. The other two sources are well defined in the LoTSS images and do not appear amorphous in shape.

Morphology is used to determine restarting sources, especially in the case of double-double radio galaxies (DDRG). In these radio sources there can be seen a brighter pair of inner lobes surrounded by an outer pair of faded, extended lobes (Schoenmakers et al. 2000, Konar et al. 2013, Kuźmicz et al. 2017, Mahatma et al. 2019). From Figure 5-1 and Figure 5-5, ILTJ113626.52 and ILTJ133729.25 are restarter candidates due to the double-double morphology that can be identified in the higher resolution VLA images. As a greater level of detail can be seen in the central core region two inner lobes have been identified. Similarly, ILTJ144650.49 also displays the possibility of inner lobes in the higher resolution images and may be categorised as a possible restarter candidate using the morphology criterion.
5.4.4.5 Remnants and restarters: Summary and discussion

Classifying a radio galaxy as a remnant or restarting source is challenging, and there are many different criteria by which radio sources can be assessed. These criteria have been discussed in detail in Sections 5.4.4.1 to 5.4.4.4. Table 5-11 lists each source that satisfies at least one of the criteria and the criteria; the details of which are given in each section. The final column lists any key points related to the source.

Table 5-11 – Summary of the individual sources meeting each criteria described in Sections 5.4.4.1 to 5.4.4.4. The sources discussed in each section are listed in the first column, and the criteria which they meet are given in the second column. Any key points relating the sources and discussed in each section are listed in the final column.

<table>
<thead>
<tr>
<th>SOURCE NAME</th>
<th>CRITERIA</th>
<th>KEY POINTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILTJ105946.75</td>
<td>USS / Morphology</td>
<td>Integrated spectral index is a lower limit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amorphous morphology</td>
</tr>
<tr>
<td>ILTJ112015.05</td>
<td>USS / Morphology</td>
<td>Integrated spectral index is a lower limit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amorphous morphology</td>
</tr>
<tr>
<td>ILTJ113626.52</td>
<td>Morphology / CP</td>
<td>DDRG - Two clear central core regions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CP still in range for active radio galaxy</td>
</tr>
<tr>
<td>ILTJ114351.49</td>
<td>USS</td>
<td>Integrated spectral index included if relaxed to &gt; 1.1, is a lower limit</td>
</tr>
<tr>
<td>ILTJ133701.52</td>
<td>Morphology</td>
<td>DDRG - Two clear central coreregions</td>
</tr>
<tr>
<td>ILTJ134315.98</td>
<td>Morphology / USS</td>
<td>Amorphous morphology</td>
</tr>
<tr>
<td></td>
<td>USS</td>
<td>Integrated spectral index is a lower limit</td>
</tr>
<tr>
<td>ILTJ144644.12</td>
<td>USS</td>
<td>Integrated spectral index included if relaxed to &gt; 1.1, is a lower limit</td>
</tr>
<tr>
<td>ILTJ144650.49</td>
<td>Morphology</td>
<td>No clear DD inner lobes – potential restarter</td>
</tr>
<tr>
<td>ILTJ145936.33</td>
<td>USS / Morphology</td>
<td>Integrated spectral index is a lower limit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amorphous morphology</td>
</tr>
</tbody>
</table>
In summary:

(i) Two sources, ILTJ113626.52 and ILTJ133729.25, have double-double morphology and ILTJ144650.49 is a possible restarter candidate with no clear double-double morphology but a clear core and a comparatively steep core integrated spectral index matching the two DDRGs.

(ii) The four sources ILTJ113626.52, ILTJ115011.27, ILTJ133729.25, and ILTJ144650.49 have all demonstrated a higher core spectral index.

(iii) Six sources, ILTJ105946.75, ILTJ112015.05, ILTJ114351.49, ILTJ134315.98, ILTJ144644.12 and ILTJ145936.33 meet the USS criterion.

(iv) Four of the USS sources can also be classified as having a relaxed or amorphous morphology. These are ILTJ105946.75, ILTJ112015.05, ILTJ134315.98 and ILTJ145936.33. ILTJ130109.83 has no compact structures in either the low or high frequency images, however its morphology is too defined to be considered amorphous.

(v) ILTJ113626.52 was noted for its low outlying CP. Its value is still within range for an active radio galaxy; however, it clearly has a double-double core feature and is a restarting radio galaxy.

(vi) No sources have been selected on the SPC criterion.

(vii) Therefore, approximately 15.8 $^{+2.6}_{-1.1}$ % (3) of the population are restarting candidates and 31.6 $^{+2.6}_{-1.6}$ % (6) are possible remnant candidates. Most of these meet the criterion of USS on a lower limit and an amorphous morphology in the LoTSS image.
5.5 CONCLUSIONS

Mingo et al. (2019) discovered a population of low luminosity FRIIs in LoTSS DR1. In this chapter I have explored the properties of this population using a sample of 19 sources at least one magnitude below the traditional luminosity break. These sources were observed with the VLA in the L-Band using the A and B configurations. The data was then processed as in Section 2.3 to produce high frequency (1.5 GHz), higher resolution (1.3 arcsec) images for comparison. I have presented these images alongside their LoTSS and FIRST counterparts and selected a group of FRII-highs to have a comparison sample of the higher luminosity population. I proceeded to do a thorough examination of both samples and demonstrated that they are reasonably representative of their respective populations allowing me to compare their properties and discuss the likelihood of any remnant or restarting classifications.

In this chapter I have been able to draw the following conclusions:

(i) When comparing the FRII-low sample to the full FRII-low population this highlighted the reclassification of 9 of the sample sources to hybrids or FRIIs with the newer DR2 images. The FRII-highs are a well-matched sample, the FRII-lows do not contain any selection biases that will affect the remaining conclusions in this chapter

(ii) There is a distinction in morphology between the FRII-highs and -lows, with the FRII-low sample containing 92 $^{+9}_{-8}$ % of sources with compact features and the FRII-high sample 60 $^{+23}_{-29}$ %. The FRII-lows have a higher prevalence of cores with 47 $^{+21}_{-20}$ % of the sources having cores and none in the FRII-highs. In contrast the FRII-highs have a higher prevalence of hotspots with 60 $^{+23}_{-20}$ % in the sample compared to the FRII-lows 26 $^{+23}_{-15}$ %

(iii) There is also the possibility of jet features in 11 $^{+22}_{-9}$ % of the FRII-lows. These features could demonstrate a change in morphological classification at higher frequencies

(iv) The integrated spectral indices from LoTSS to the VLA, $\alpha_{1500}^{15}$, span the range of ~0.5 to 1.0 for all sources where it is not a lower limit. This is typical for active radio galaxies. About half of these sources are in the range of 0.7 to 1.0 which is typical for FRII-highs and matches the results from Mingo et al. (2019). There are six sources whose integrated spectral indices had to be calculated as lower limits and they all lie out of
this range, with values of $a_{\frac{1500}{150}} > 1.1$. The three sources that contain double core features and an elongated core all have high core integrated spectral indices compared to the sources with compact circular cores.

(v) When divided into sub-groups by host galaxy optical magnitude and radio luminosity the sub-group containing the sources with the lowest host galaxy magnitude and radio luminosity has the highest percentage of compact features, $86 \pm 14\%$. The sub-group with the highest host galaxy magnitude and radio luminosity and hence most likely to have source dynamics similar to the FRII-highs has the lowest percentage of compact features, $50 \pm 29\%$. This could be due to low powered jets in a weak environment. The uncertainties are large enough on these small samples that any differences are tentative and not statistically significant.

(vi) I have identified 6 new remnant candidates and 3 new candidate restarting sources using the criteria set out by Jurlin et al. (2021). This gives $32 \pm 23\%$ of the population of FRII-lows which are remnant candidates and $16 \pm 23\%$ which are restarting candidates.

As mentioned previously 9 of the sources were re-classified with the newer DR2 images, and this may have had an impact on the results. However, the determination of compact features is not affected by the classification and so has no effect on these results. Three of the re-classified sources (ILTJ113626.52, ILTJ144650.49, and ILTJ145936.33) have been classed as restarting or remnant candidates. In the case of ILTJ113626.52 and ILTJ144650.49 the re-classification will possibly have been due to their elongated core features in LOFAR. For ILTJ113626.52 the double core feature is clear in the VLA image, whereas ILTJ144650.49 is only a possible candidate. ILTJ145936.33 was selected through an USS and an amorphous morphology and is clearly edge-brightened in the LoTSS images. There is the possibility that this could affect the number of restarters and remnant candidates.

Thirteen of the sources were observed at C configuration as their LAS is over 60 arcsec. Four of these thirteen sources are only just over the 60 arcsec size requirement, so the C configuration data will have less of an impact. These include ILTJ112015.05 and ILTJ1133729.25 from the remnant and restarting candidates. There are six more of these sources which are twice as large (one is three times as large) as 60 arcsec, therefore the inclusion of the C configuration data is more likely to have an impact on the images. Included in these are two non-detections ILTJ114351.49 and ILTJ145936.33 which have been classified as remnant candidates, and the restarting candidate ILTJ113626.52. The inclusion
of the C configuration data may increase the flux density in the region and flatten the integrated spectral indices for these sources. For the USS sources some of them are borderline at $\alpha \gtrsim 1.1$ and therefore the C configuration data could have an effect on the remnant candidate population.

My results highlight the fact that changing frequencies and resolution can affect the morphological classification of a source and what looks to be a low luminosity FRII in LoTSS, due to low resolution and dynamic range, may very well be a hybrid or FRI source when observed at a higher frequency or resolution. These higher frequency, higher resolution images for the sample of 19 FRII-lows have demonstrated a diverse population including active radio galaxies and possible restarting and remnant sources.
6 Future Work

"Are you seriously telling me that your plan to save the universe is based on 'Back to the Future'?'"

Tony Stark, Marvel’s, Avengers: Endgame

The previous chapters have presented the main science analysis that I have undertaken. The focus of this chapter is to summarise several smaller projects and areas of ongoing development, as well as future research activities. This chapter has two main sections, which address my ongoing and future plans for RL-XID and the FRII-low population.

Section 6.1 follows the work from Chapters 3 and 4 on RL-XID. In those two chapters I described the development of RL-XID and its application to the LOFAR Two-metre Sky Survey (LoTSS) DR1 data set. In Chapter 3 I detailed the ridgeline drawing process and in Chapter 4 I used the outcomes in the likelihood ratio (LR) code to find the optical host, and compare my predictions with that of citizen science classifications via LOFAR Galaxy Zoo (LGZ). The results of RL-XID are comparable to LGZ for both the chosen sample of large and bright sources and for the full set of LoTSS DR1 sources. RL-XID was created with the aim of improving the automated likelihood ratio method for the extended radio sources so that the reliance on projects such as LGZ is reduced. This is important because in LoTSS DR1 roughly 12,000 sources were selected for optical host identification from the ~320,000 sources in the 424 deg$^2$ covered. In LoTSS Data Release 2 there are roughly 4 million sources in the ~5600 deg$^2$ surveyed. For LoTSS DR2 and other large radio surveys such as those with the Square Kilometre Array (SKA) (see Section 1.9), an automated method will greatly reduce the amount of time and resources needed for the host identification process.

It follows naturally from here that the subsequent work that I have been pursuing focuses on readying RL-XID for automation. In Section 6.1.1 I address the modifications made to RL-XID to allow it to successfully cross-identify for LoTSS DR2. I am continuing to apply these adjustments further, in Section 6.1.2, by working collaboratively to incorporate RL-XID as part of an automated
pipeline. This pipeline will bring together the main aspects of the LGZ method and is a first attempt at a fully automated association and identification pipeline. Automating the decision tree from Williams et al. (2019), association of sources, and cross-identification is key. It will reduce the time and chance of error in the citizen science led results, not only for LOFAR (and LoTSS) but for other large upcoming surveys, therefore adaptability is a vital feature. In Section 6.1.3, I explain how I have worked to adapt the code for the MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE) survey (Jarvis et al. 2016). This deep survey produces images able to detect extended emission and is similar in resolution to LoTSS; see Section 2.4. As it is also a precursor to the SKA this makes it an ideal data set to test RL-XID.

Having identified host galaxies for radio sources means we are able to associate their properties and look at different populations in detail. In Chapter 5 I studied a newly discovered population of FRII-lows further, which contained some interesting sub-populations including both active and restarting radio galaxies. There are many ways in which I can continue this work, and in Section 6.2 I discuss potential avenues to do so, considering the whole sample.

Having used the VLA Sky Survey (VLASS) quick look images in Section 5.4.4.2 to try and determine the spectral curvature of the sample sources, Section 6.2.2 is a reminder that these images are not without their limitations. One obvious future step is to improve the work in Section 5.4.4.2 by using the better quality, single-epoch images, when they become available, with the anticipation that the better flux calibration may reveal more extend emission. Having looked for evidence of older, fading sources using integrated spectral indices, Section 6.2.3 highlights how I can advance this using spectral maps to determine how the spectral index varies across the whole of the radio source. Future work can also be carried out on the remaining data sets, which can still be processed into images. This is covered in Section 6.2.1.

The identification of several candidate double-double radio galaxies (see Section 5.4.4.4) opens another opportunity for my future research. In Section 6.3 I discuss different ways in which I can investigate these individual sources to confirm their double-double (and hence restarting) nature. These different future research ideas are summarised in Section 6.5.
6.1 Future Applications of RL-Xid

The purpose of creating RL-Xid was to build an effective piece of automated software that enables the likelihood ratio (LR) method to be applied to extended sources and reduce the need to send the more complicated sources to the citizen science project LOFAR Galaxy Zoo (LGZ), hence reducing the cost in time and human resources. With RL-Xid producing results which are comparable to those of LGZ for DR1 (see Section 4.2.5) the following sections discuss which future applications of RL-Xid I have already started to implement.

6.1.1 Data Release 2

As the aim was to have an effective, automated method for cross-identifying host galaxies, applying RL-Xid to LoTSS DR2 allowed for it to be applied in the manner it was intended: to analyse an unidentified catalogue. As data release 2 (DR2) of the LOFAR Two-metre Sky Survey (LoTSS) was in the process of being cross-identified through LGZ44 until summer 2022, it made a perfect data set to run and test RL-Xid on. In LoTSS DR2 LGZ plays an important role in the association of components to form large radio galaxies, as well as detecting and handling sources defined as ‘too zoomed in’ or ‘blends’. Due to optimising the process for speed, the volunteer classifications did not include the WISE information, but this could be included in an automated ridgeline run for DR2. The reliability of the citizen science results in DR2 is reduced due to the classifications being performed by the public rather than the expert volunteers used in DR1.

In order to apply RL-Xid, various changes had to be made to the code to adapt for differences between data releases, and to account for the fact that the outputs were no longer being compared to a known catalogue. This task was time constrained, as the outputs were being used to identify targets for spectroscopic follow-up with the WEAVE-LOFAR Survey (Smith et al. 2016) to enable accurate redshift determinations. This time constraint, combined with the impact on the PhD due to Covid, led to much of the batch running and by-eye checking being performed by Judith Croston.

One of the most important input parameters to RL-XiD is source size (see Section 3.2). Among other factors, it is used to determine the maximum length of the ridgelines, and when they are permitted to jump gaps in emission. For the DR1 sample all the sizes were pre-determined using LoMorph (see Section 2.1, and Mingo et al. 2019). For DR2 these sizes were not pre-calculated and, as the aim was to remove the dependency on LGZ, any catalogued size determination from sources pre-associated with LGZ could not be used. Therefore, I applied a modified version of the size calculation algorithm within LoMorph (Mingo et al. 2019) at the start of RL-XiD. To apply the new size calculations the FloodFill and Masking functions were updated to match the newer version from LoMorph applied to the LOFAR Deep Fields (Mingo et al. 2022). Running this newer version of the FloodFill and Masking both before the size calculations and during the ridgeline drawing process, has reduced the number of sources that were failing due to catalogue errors. The addition of the size calculation before commencing with the ridgeline drawing aspect of RL-XiD now catches any non-matching component associations between catalogues.

The other significant difference between running RL-XiD on DR1 and DR2 is the final output required. For DR1 I was comparing the identified hosts with a known solution set to see how well the code performed. This allowed for a simple yes/no match output and permitted the use of a known identifier column throughout the cross-identification process. In DR2 the output needs to be a list of the identified possible host for each source. This led me to having to adjust the code so the tables would need to match on a column other than their unique identifier (allocated in DR1 by their cross-matched host). As not every possible optical source was guaranteed to have either a WISE or LEGACY identifier, I chose to match the sources on their RA to seven decimal places. Once the sources from all the catalogues could be successfully matched the output becomes a list of RA and DEC positions of the most likely matches to each source. Along with this, the choice is there to include any source identifiers, or the LR for checking against the set threshold. As discussed in detail later, a threshold is put in place to select the most likely host galaxy candidates and to set boundaries on the reliability of the code’s outcomes.
One of the most significant changes between DR1 and DR2 is the update in optical/IR catalogues from PanSTARRS and AllWISE to LEGACY\textsuperscript{45} and unWISE\textsuperscript{46} (Schlafly et al. 2019). The LEGACY survey covers the North Galactic Cap in the $ugriz$ with magnitudes of 22.0, 22.2, 22.2, 21.3 and 20.5, and its PSF has a median of 1.4 arcsec in $r$\textsuperscript{46}. The unWISE catalogue (Schlafly et al. 2019) contains deeper images than AllWISE, and at 5\(\sigma\) is able to detect sources \(\sim\)0.7 magnitudes fainter. Relative to AllWISE, it has greatly increased the number of galaxies detected up to redshift 2, which is crucial for cross identification\textsuperscript{47}. This change created a couple of instances where RL-X\(\varnothing\) needed to be adjusted to make the calculations and a-priori data sets compatible with the new catalogues. The most noticeable difference was a variation in the spread in magnitude distributions for the candidate host galaxy population in DR1 and those in DR2. Since the LEGACY/unWISE catalogue was using the $r$-band data instead of the $i$-band data used previously in DR1, I modified the code accordingly. As described in Chapter 4, \(q(m, c)\) in Eq. 4-3 is a kernel density estimator representing the magnitudes (and colours) of the extended radio galaxies from the original LGZ sample. These magnitudes (and colours) needed to be converted to the $r$-band as the DR2 catalogue requires. To do this I applied an adjustment of +0.33 to convert the $i$-band values to $r$-band. A further difference is due to the LEGACY/unWISE data using luptitudes\textsuperscript{48} (Lupton et al. 1999), so I converted the optical catalogue to the same magnitude system before commencing with the LR.

In DR1 the PanSTARRS/AllWISE optical catalogue had positional errors associated with each source (see Section 3.1), this is not the case for LEGACY/unWISE. Therefore, I calculated the mean of the errors in PanSTARRS/AllWISE and applied a value of 0.2 as the uniform error for DR2. Further, minor changes were necessary to help eliminate any possible instances where zero values or null outcomes might be produced, creating new failure points in the code. These are unlikely to have occurred previously, because for DR1 the code could match with known outcomes. In DR2 there is an opportunity for missing magnitude information, or for no candidate hosts to be selected.

\textsuperscript{45} https://classic.sdss.org/legacy/index.html
\textsuperscript{46} https://catalog.unwise.me/catalogs.html
\textsuperscript{47} https://irsa.ipac.caltech.edu/data/WISE/unWISE/gator_docs/unwise_colDescriptions.html
\textsuperscript{48} https://ned.ipac.caltech.edu/help/sdss/dr6/photometry.html
The normalisation factor within Eq. 4-3 (see Section 4.2) was adjusted to better reflect the use of both the centroid separation and the ridgeline separation, giving a search density in \( n(m, c) \) as a combination of both one- and two-dimensions. This change in the normalisation factor allows for a better threshold selection (discussed below).

Finally, due to the significantly higher number of sources in DR2 (leading to a larger quantity being sent for classification via LGZ and RL-XID) some additional batching code was written by a collaborator (M. Hardcastle). This has altered how the sky area is calculated to fit for the size of the batched catalogue. It uses healpix to batch the sky into local grids rather than set trapeziums based on RA and DEC. With the success of these changes increasing the speed at which RL-XID runs, these batched runs are now being implemented on LoTSS DR2 (Shimwell et al. 2022; Hardcastle et al. in prep.).

The test field selected was the v1.0 Spring60-65 (which covers 135° < ra < 250° and 60° < dec < 65°, \( \sim 110 \text{ deg}^2 \)) and the sources were not prefiltered for those considered ‘too zoomed in’ (individual components of a radio source) and ‘blends’ (multiple sources intertwined). The test field was run multiple times with combinations of two different size (\( \theta > 15 \text{ arcsec} \) and \( \theta > 25 \text{ arcsec} \)) and flux (\( S > 10 \text{ mJy} \) and \( S > 30 \text{ mJy} \)) minimums. Then three possible thresholds were put in place for each group (\( LR > 1, LR > 5 \times 10^3, LR > 1 \times 10^6 \)) below which hosts were discarded.

For each group, the hosts were selected over each threshold, 100 sources were then chosen to be checked by-eye. There are different possible outcomes resulting from these checks depending on the reliability desired, and the threshold taken. If the highest threshold is taken when combining the LGZ and RL-XID identifications, and a reliability of > 85% is acceptable then the number of identified hosts increases from 33% (with just LGZ) to 55% (using both LGZ and RL-XID combined) for all sources > 10 mJy and > 15 arcseconds. If a reliability of 90% is preferred, a higher flux cut is taken and the number of identified sources increases from 31% (LGZ) to 56% (both).
Figure 6-1 – A comparison of the (a) flux (mJy) and (b) size (arcsecond) of the sources in LoTSS DR2 grouped by their host identification method. The lines are the fraction of the identifications determined by each method for the given size and flux density. Catalogue courtesy of M. Hardcastle and is described by Hardcastle et al. (in prep.).
Figure 6-1 shows a comparison of the total fluxes (mJy) and major axis sizes (arcsec) for each method of host identification in LoTSS DR2. In the first released catalogue, described by Hardcastle et al. (in prep.), ~36,000 sources have had their hosts identified using RL-XID. As described in Chapter 4 RL-XID performs best on the largest and brightest sources compared to the LR which works best on small, compact sources. This is demonstrated in Figure 6-1 with the number of identified hosts using RL-XID increasing towards the higher fluxes and sizes, and the LR decreasing. As was mentioned previously the application of both RL-XID and LGZ approximately doubled the number of hosts identified compared to just LGZ alone, and this is demonstrated in the flux graph where they both increase together. The graphs underestimate what proportion of identifications could have used RL-XID, as there is a number of large sources that were visually checked. In the cases where there were both LGZ and RL-XID classifications the LGZ host identification was chosen.

One area that I can explore in the future is the formalisation and refinement of the completeness and reliability of RL-XID. This can include checking its success rate on a sample which does not include the ‘too zoomed in’ and ‘blended’ sources. These sources will have to go through pre-selection and possible filtering before cross-identifying, be this through automated methods or LGZ, and may not be included in the final set of sources to go to RL-XID. Methods similar to those used by Williams et al. (2019) may be applicable in constraining the threshold, and reliability and completeness, for a given size and flux. Applying a combination of these should prove to give a more reliable solution set.

### 6.1.2 **Automated pipeline**

As discussed in Section 2.1 Williams et al. (2019) use a decision tree to determine which sources can have their hosts identified through the LR method and which need to be passed to LGZ. Most of the sources being handled by LGZ are the extended, large, and bright sources. However, some have been designated as more complex sources and require visual inspection. At this point LGZ does not just identify hosts, it also allows for experts to be notified about more interesting cases and deal with them accordingly.
Within LGZ a large source can have many of its individual PyBDSF components associated with each other (see Section 2.1.4) (Mohan & Rafferty 2015). Here, small patches of emission that look like individual sources but are part of a larger source, are linked together as one. In some instances, the image of the region can be ‘too zoomed in’ on a single component that should clearly be part of an extended radio galaxy. Likewise, LGZ is the ideal platform for people to indicate instances where sources may be overlapping ‘blends’, at which point these are checked and de-blended. All the processes that are validated by experts and the extra steps that are then taken by volunteers to ensure proper association and identification of radio galaxies, take time and run the risk of human error. With larger surveys, such as LoTSS and the upcoming SKA projects, the number of sources observed is increasing. This puts an emphasis on producing effective automated methods.

As previously mentioned, RL-XID was created with the aim of improving the automated LR for extended sources and reducing the need for platforms such as LGZ. However, RL-XID requires the initial steps of the identification process to occur before it can run successfully. It needs to know which sources have been selected to go to LGZ (as they are most likely the extended radio galaxies) and it needs any association of components into individual sources to be done. This association is currently still being done through LGZ.

It is anticipated that a fully automated pipeline can be produced going through the decision tree phase, association of components for larger sources and finishing with cross-identification. I have currently started working with Lara Alegre, Huib Intema, and Rafaël Mostert regarding integrating our three automated methods into a single working pipeline. Lara has produced a machine learning classifier which incorporates the results of the original LR and determines which sources are likely to need association (or possible handling by LGZ) (Alegre et al. 2022), and Rafaël has used a convolutional neural network to associate radio source components (Mostert et al. 2022). A working combination of our three methods will remove most of the dependency on LGZ.

There are still areas to be addressed. The process by which the ‘too zoomed in’ and ‘blended’ sources are detected in LGZ is not currently handled. This will lead to an increase in failed outputs or reduced reliability from RL-XID. Once all three codes have been successfully linked together, work will have to be done on testing the completeness and reliability of the outcomes. Given the different nature of the codes this could be done in different ways. Currently, even if a
combined version of our automated methods existed, LGZ would still be required. There is the possibility of sources being passed to RL-XID which have not been associated, or are 'too zoomed in', as well as those classed as 'blends'. There may even be those which cannot be identified by the original LR and are below the chosen flux and size requirements of RL-XID. In these instances, LGZ is still required to associate, de-blend, or cross-identify complex sources. Therefore, initially, the automated code needs to work with LGZ to achieve the maximum number of identified sources. A simplified summary of the automated pipeline workflow is given in Figure 6-2.

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**Figure 6-2** – A simplified workflow of the automated pipeline. The yellow boxes show the automated processes, including the initial inputs from Williams et al. (2019)'s original LR. The successful outcomes are indicated with a solid blue arrow, and any unsuccessful outcomes are marked with a dashed orange arrow. DR2 is currently being associated and cross identified through LGZ and this has been included in the red box.
LOFAR is not the only telescope whose surveys need to have host identification to study radio galaxies in more depth. To this end the ability to apply RL-XID to other survey data is important, as it will allow the opportunity to determine host galaxies for extended sources in a variety of surveys covering different locations and frequencies. To see how adaptable RL-XID is, I applied it to a data set from the MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE) survey, which is a deep continuum which detects extended emission and produces images similar to those from LoTSS (see Section 2.4) (Hale et al. 2022; Heywood et al. 2022; Whittam et al. 2022). As the MIGHTEE data is more similar to the SKA surveys than LOFAR, this makes it an ideal survey to test RL-XID on. My sample data is taken from the XMM-LSS field.

Similar to the previous work done with LoTSS DR2, my initial aim was to get the code to work with the new data set as successfully as possible. This means I had to apply various adjustments to the code to accommodate the different data sets. These have been discussed in detail below.

As the step and search cone size can be determined by the user (see Section 3.2.2) these can be easily adjusted for preference and survey. However, there are constants which are survey specific and need to be changed in the constants file. These include the arcsecond to pixel ratio which is crucial for getting the size conversions correct. This is also important for checking the beam size. Beam size can affect the chosen step size (in pixels) and the masking sizes used during the ridgeline drawing process. Masks that are too large or too small may affect the code’s ability to select suitable points.

As well as making sure the survey constants are correct, a few minor adjustments had to be made for differences in the catalogues. There were two significant differences between LoTSS and MIGHTEE. Firstly, MIGHTEE covers the southern hemisphere and therefore has negative coordinates, previously unaccounted for within RL-XID, but crucial for dealing with centroid location.
Figure 6-3 – Six MIGHTEE sources with ridgelines drawn. Radio images courtesy of I. Heywood.
Secondly, a unit check was added to make RL-XID compatible. This has been noted in detail in the appropriate functions in RL-XID. Having made these adjustments to RL-XID the initial ridgeline section of the code was run. This produced successful ridgelines for the MIGHTEE data (see Figure 6-3).

At the time of writing, I am working with the initial catalogue for the data set, and one area of interest is whether there were large sources that needed to be associated in the mosaic, and whether it might be possible to improve on the number of sources identified in the initial catalogue. Sources are found in a similar fashion to LoTSS by searching for smaller components first before determining if they need associating into larger extended sources. To investigate this, I started working with PyBDSF, see Section 2.1 (Mohan & Rafferty 2015) with the aim of identifying sources in the mosaic and determining how many may need associating. I started by using the LoTSS inputs for the source finding parameters but changing the survey inputs to match MIGHTEE (see Section 2.4). This led me, after by-eye checks, to a final sample containing \(~3\) extended sources that would need associating, and a large proportion of the \(~200\) sample as repeated sources. This is where the brighter centre emission is identified as a separate source to the extended outer emission. These source detections make it quite hard to run RL-XID in its current form without manual filtering, as they will create duplicates in the solutions.

There is continuing work to produce more up to date MIGHTEE catalogues which have undergone their own further testing and modifying with PyBDSF to detect sources. Combining these with the now completed RL-XID for DR2 is the next stages of cross-identifying with the MIGHTEE data. However, these new catalogues will have to be checked to see if the extended source components have been associated. Also, like DR2, extensive work will need to be carried out to test the completeness and reliability and to determine a suitable threshold which maximises both. I can implement this in the same way as for LoTSS DR2 or look at other methods, such as those by Williams et al. (2019)
6.2 Investigating the FRII-Low Population Further

In Chapter 5 I investigated a sample of FRII-lows discovered in LoTSS DR1, by following them up with observations made with the Karl G Jansky Very Large Array (VLA), see Section 2.2. The aim of this work was to see if the low-luminosity FRIIs have similar source dynamics to the traditional high-luminosity FRIIs. The higher frequency, higher resolution images allowed me to explore the prevalence of compact features in each population and to look at factors such as their integrated spectral indices. These properties showed a population containing a mix of active and restarting radio galaxies, with the possibility of finding radio galaxies during their remnant phase. In the following sections I discuss how I can continue to investigate the low luminosity radio galaxy population further. This can be explored by considering the sample as a whole or by studying individual sources in detail.

6.2.1 Additional Observation Data

The final VLA images I produced of the FRII-low sample for Chapter 5 are of the observations taken in the L band using configurations A and B, discussed in Sections 2.2.1 and 5.2. These were used because the A configuration would highlight compact features and give a higher resolution image, whilst the B configuration would give a resolution complementary to LoTSS and would capture more of the extended emission. These two configurations allowed for the comparison of morphological features and analysis of spectral properties. However, these were not the only observations of the FRII-lows taken as part of the original science proposal. As well as the L band A and B configurations there are two further observation data sets which I can reduce as in Section 2.3.

Although the two data sets used cover many of the aims discussed in Chapter 5, the addition of the L band C configuration, and C band data will increase our understanding of the FRII-low population. The C configuration data complements the A and B configurations for the largest sources, ensuring that all of the extended structure has been observed, and the C band data captures the compact features at a higher frequency. Both of these are crucial to the
spectral analysis work and will help confirm the numbers of active, restarting and remnant sources in the sample.

Observations were also taken in the C band using the B configuration. These are higher frequency observations at 6 GHz and would have a resolution of ~1 arcsec. As these are higher frequency from the L band observations and higher resolution then I can use them to investigate the prevalence of compact features of the sources further. This would be particularly useful for the remnants and restarters, allowing a more detailed study of the differences between the central components. How many morphological features that can be seen at higher frequencies will help explore the number of low-luminosity, active FRIIs in the population. Many of the same properties explored in Chapter 5 can be re-visited with this added data set.

The L band C configuration was requested for 13 of the targets in the sample who are known to have largest angular scale (LAS) > 1 arcmin, See Section 5.2, Table 5-1. These observations will have a lower resolution at ~14 arcsec and are better at detecting extended emission on larger scales. They have been included to ensure that the sources with the largest structures can be fully observed. If I were to combine this information with the A and B configuration images this would give a more complete picture of the extended emission in the lobes for the larger sources, bringing them in line with the images obtained from LoTSS. This is important for spectral analysis; with this information I would be able to produce more accurate spectral indices. This would also work well with any application of the software BRATS\(^\text{49}\) (Harwood et al. 2013, Harwood et al. 2015). This is a program which is able to produce spectral ageing maps for radio sources. These images will tell me the age of the emission across the source, demonstrating how it changes (see Section 1.3). In order to do this, as much of the extended emission as possible is needed for more accurate results.

\(^{49}\) http://www.askanastronomer.co.uk/brats/
6.2.2 **Improving the VLASS Images**

There are many ways in which the work in Chapter 5 can be extended through investigating the full sample of 19 FRII-lows further. In this section I discuss how to use higher quality, higher frequency images can increase our understanding of the FRII-low population by improving the work on spectral analysis and helping to confirm the number of restarter and remnant sources.

As discussed in Section 5.4.4.2, the VLA Sky Survey (VLASS) quick look images were used to calculate spectral curvature. As mentioned, these images can have limitations due to dynamic range and peak flux densities which may impact the total integrated spectral index for extended sources. Ideally, the single-epoch (science-ready) images should be used instead, as these have been properly self-calibrated. The single-epoch images of ~1000 deg$^2$ were made available at the end of 2022, and previously there was only ~500 deg$^2$ of unreleased prototype images. I have been lucky enough to have access to the prototype images to see if any of the 19 sample sources are single-epoch images. However, the currently available ~500 deg$^2$ is only a fraction of the ~34,000 deg$^2$ planned for the final VLASS data release, and unfortunately only two of the sample sources have been processed.

Of these two sources ILTJ133217.44+484221.7 is the source that shows a clearest FRII morphology (see Figure 5-1 (j)) and in Figure 6-4 the difference between the quick look and single-epoch image is shown.

To investigate whether there is a significant improvement in the images I checked the signal-to-noise ratio (SNR) for the two hotspots. To do this I placed two circles of radius 6 arcsecs, one on each hotspot, and two rectangles in areas around the source that appear to be clear of source-related emission, in each image.

Using DS9 I determined the peak emission in the hotspot circles, and the average RMS in the rectangles. I checked the RMS for both the quick look and single-epoch image using CASA and they differ from the DS9 value within a few $\times 10^{-6}$ Jy. The RMS was calculated with these rectangles near the source. As the single-epoch image is a full 1 deg$^2$ the additional surrounding sources may affect the overall RMS value of the image, however these images have been through the self-calibration process so should have dealt with any noise effects. The DS9 RMS value is close enough to the CASA value to check whether there is a change in the SNR.
Figure 6-4 – The VLASS (a) quick look and (b) single-epoch images for ILTJ133217.44+484221.7. In each image the regions used to determine the SNR are shown. The two cyan circles over the hotspots have a 6 arcsecond radius and are used for determining the peak emission of each. The two yellow rectangles are used to calculate an average RMS for the image. Image (b) courtesy of Mark Lacy, NRAO, Project Director, with thanks to Yjan Gordon, personal correspondence, 27/6/22.
Table 6-1 shows the SNR of each of the hotspots in both the quick look and the single-epoch images. The last column shows that the SNR has increased between 5% and 10% in the single-epoch image, as well as the background looking smoother in Figure 6-4. However, there is some possible lowering of detected emission from the quick look image. This indicates that the single-epoch images might be slightly better, even though these sources are fainter.

Table 6-1 – The average RMS and hotspot peak values of the quick look and single-epoch images for calculating the SNR difference. The hotspots are taken from the left to right cyan circles in Figure 6-4.

<table>
<thead>
<tr>
<th>HOTSPOT REGIONS</th>
<th>AVERAGE RMS (Jy/beam)</th>
<th>HOTSPOT PEAK VALUE (Jy)</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>QL LEFT</td>
<td>$1.64 \times 10^{-4}$</td>
<td>$8.52 \times 10^{-4}$</td>
<td>5.19</td>
</tr>
<tr>
<td>QL RIGHT</td>
<td>$7.78 \times 10^{-4}$</td>
<td>$4.73$</td>
<td></td>
</tr>
<tr>
<td>SE LEFT</td>
<td>$1.48 \times 10^{-4}$</td>
<td>$8.47 \times 10^{-4}$</td>
<td>5.72</td>
</tr>
<tr>
<td>SE RIGHT</td>
<td>$7.42 \times 10^{-4}$</td>
<td>$5.01$</td>
<td></td>
</tr>
</tbody>
</table>

With access in the future to single-epoch images for all 19 sources in the sample I should be able to produce more accurate integrated spectral indices involving these higher frequencies, provided VLASS can detect the same emission as LoTSS and the VLA. From here I should be able to calculate the spectral curvature parameter to a greater degree of accuracy and determine whether any of the sample sources are showing signs of being a radio galaxy that has recently switched off but is not yet detectable via an ultra-steep spectrum in the lower frequencies.

### 6.2.3 Spectral Ageing Maps

In Section 5.4.1.3 I investigated the integrated spectral index properties of the 19 FRII-lows. The integrated spectral index provides an indication towards the age of a radio source, as the steeper the spectral index the older the emission (see Section 1.3). These calculations were carried out to identify possible remnant candidates within the sample. To achieve this, I calculated separate integrated spectral indices for the cores and lobes of the sources, where cores were present in the VLA observations. Here the intention was to find any
sources where the lobe/core spectral indices might show a substantial difference. If this were the case, the lobes may be significantly older than the core, possibly indicating a restarting source.

My future work can improve on this simple check by producing spectral ageing maps using BRATS (Harwood et al. 2013, Harwood et al. 2015). With this more detailed information on the ages of the individual radio sources, investigating any differences between the core and lobes will be easier. This will allow me to determine any sources that might be classed as remnant or restarting.

6.3 Explorer a Double – Double Source

Having discussed the future prospects for the full sample, this section will focus on the research I can undertake concentrating on a single source (or two) from the whole sample. Part of the aims from Chapter 5 was to understand how large the proportion of older, fading radio sources in the FRII-low population might be. To this extent the existence of possible remnant or restarting sources was explored. Radio galaxies with a double-double morphology (DDRG) are considered restarting sources. DDRG have an outer, fainter pair of lobes corresponding to an older episode of emission, and a smaller, more recently produced inner set (Schoenmakers et al. 2000, Konar et al. 2013, Kuźmicz et al. 2017, Mahatma et al. 2019). This is seen in source ILTJ113626.52 and ILTJ133729.25, and Figure 6-5, where ILTJ144650.49 has also been presented as a possible restarter.

All three sources are excellent candidates for further detailed spectral analysis using BRATS. ILTJ113626.52 and ILTJ133729.25 have a large amount of clear, extended emission and will give a comprehensive spectral ageing map. For both of these sources there is C configuration data available (see Section 6.2.1) as they have an LAS > 1 arcmin. This is also true for ILTJ144650.49. The use of these datasets will ensure that the largest structures are fully sampled, including more of the flux. This may flatten their integrated spectral index, but they have not been classed via the USS criteria. These datasets will also allow me to determine the difference in age between the central region and the outer lobes, and how the spectral age can change across the source itself. This could answer
the question of whether the centre is significantly younger, as would be expected for a restarting source. Alternatively, this may indicate other explanations such as projection. The spectral maps may highlight any areas in the lobes that are active on the same time scales to the central region. The brighter regions indicating higher flux intensity, particularly in the southern lobe of ILTJ144650.49, may imply that the radio source may have never completely switched off when entering its remnant phase, or that it may be an active radio galaxy.

Figure 6-5 – Three possible restarting sources. (a) ILTJ113626.52 and (b) ILTJ133729.25 appear to have double-double morphology with two smaller lobes in the central region and (c) ILTJ144650.49 is a possible restarting candidate with the brighter central region.
One possibility I can explore in the future is proposing to observe these sources with the LOFAR long baselines. With the international baselines reaching up to ~2000 km LOFAR can reach resolutions down to ~0.3 arcsec for frequencies under 200 MHz (Morabito et al. 2022) (see Section 2.1.1). If I can produce highly detailed images of these sources, then I would have the opportunity to investigate the DDRG nature of ILTJ113626.52 and ILTJ133729.25, and study ILTJ144650.49 further.

Concentrating on the central region of ILTJ113626.52 and ILTJ133729.25 I can continue to investigate various properties of the radio galaxies. To begin with I can start by looking at the location of the host galaxy. If the host galaxy is central in the double lobe feature, then it is more likely to be a DDRG. If the host galaxy is slightly closer to one lobe than the other, then there is the possibility that the radio galaxy is at an angle to the line of sight. This will generate projection effects as one lobe will be angled away and one towards. In this instance, the lobe travelling away will appear fainter, or counter, the one moving towards may appear more active as it is brighter due to being boosted (Magliocchetti et al. 1998; Harwood et al. 2013). There is also a possibility that the central region may be brightened due to precession of the source, and that this is a feature that could be explored (Harwood et al. 2020).

Another investigative step I can take, still concentrating on the central region, is to explore its spectral properties. I can do this with just the A configuration images I produced and the VLASS images (either the quick look or single epoch if they are available). Taking the central area as a whole, if a flat integrated spectral index is evident then a core is present; if it is steeper then jet features will be present. Likewise, I can study each component in the inner double-double lobes. I can look at whether they have different integrated spectral indices, one component with a flat index and one with a steep index may indicate the presence of a core and jet feature. If it is a DDRG the expectation is that this is due to two younger jets.
6.4 Expanding on the FRII-lows

One interesting way to extend this research further is to combine all aspects of this chapter together by using the entirety of the DR2 dataset to search for a much larger sample of FRII-lows. The automated method of LoMorph (Mingo et al. 2019) can be used to classify sources as FRIIs, and RL-XID can be applied to determine their host galaxies. From here their properties such as redshift and luminosity can be determined. As most of the DR2 area has been covered by the international baselines there are high resolution datasets of many of the sources. These can help confirm the conclusions in Chapter 5 about the number of restarting candidates in the population.

6.5 Conclusions

This chapter has focused on detailing my continuing work with RL-XID and future projects that build on the work within the thesis, with both the cross-identification and the FRII-low population.

My ongoing work with RL-XID has led to it being successfully implemented in LoTSS DR2. My future endeavours with this code will concentrate on refining the outcomes, testing its adaptability, and its deployment into the automated pipeline. Working with the FRII-low population presents different prospects depending on whether the choice is to study the whole sample, focus on the interesting double-double sources, or expand to look for a larger sample of FRII-lows. There is also the prospect of RL-XID being developed further for morphological analysis.

The future research opportunities discussed in the chapter are summarised as follows:

(i) The completeness and reliability of LoTSS DR2 needs to be formalised with the possibility that better thresholds can be determined and set. This work will also need to include some strategies for handling sources that are ‘too zoomed in’ or ‘blends’

(ii) I have worked collaboratively to achieve the deployment of a fully automated pipeline involving most of the stages of cross-identification. RL-XID will be part of the process to find host galaxies that will hopefully
reduce/remove the need for projects such as LGZ. This needs the same level of formalisation as DR2 when dealing with completeness, reliability, and thresholds, and it currently also cannot handle very complex cases

(iii) Using the newer catalogues for the MIGHTEE survey, running RL-XID can be further modified for MeerKAT and assessed for how successful it is. This may run into complications if the larger sources have not been properly associated in the newer catalogues

(iv) Having access to the VLASS single-epoch images for the whole sample could lead to more accurate integrated spectral indices for higher frequencies, and more reliable spectral curvature calculations. These can be used to assess whether there are remnant candidates in the sample

(v) The software program BRATS can be used to produce spectral ageing maps. These will provide more information about the sources and details about their compact features

(vi) The individual sources ILTJ113626.52, ILTJ133729.25 and ILTJ144650.49 can be studied further, and their restarting nature investigated. The spectral ageing maps will again yield more information about the sources. It will highlight whether the central region is younger and pick out any areas of activity in the lobes

(vii) Proposing for images from the LOFAR international baselines for these sources will give high resolution images. These should confirm the presence of a double-double morphology and allow me to study the central regions in more detail

(viii) When studying the central region specifically, the host galaxy location can be investigated, as this might indicate a DDRG or a core/jet with projection effects. Detailed spectral analysis of the central region will also reveal if they are cores or jets
7 CONCLUSIONS

"As always sir, a great pleasure watching you work."

Jarvis,
Marvel's, Iron Man 3

This thesis set out to explore extended radio galaxies using LOFAR, and I have achieved this by expanding our capacity for automated identification of host galaxies. This helps detail the intrinsic properties of the radio sources and their hosts, and to build better population models. With this information, these populations can go on to be investigated further, such as the population of FRII-lows which I investigated using new VLA images. Again, a deeper understanding of the populations which are revealed by improving observational instruments can lead to a better understanding of galaxy evolution.

In Chapters 3 and 4, my work focused on RL-xid, an automated method designed to use ridgelines as part of a likelihood ratio to cross-identify the optical host galaxies with the extended radio sources. The aim of this work was to produce a method whose outcomes were comparable to the LOFAR Galaxy Zoo (LGZ) citizen science project and could be applied to current and upcoming datasets. The anticipated outcome would be to reduce the number of sources that need cross-identifying via LGZ and saving on time and manpower, whilst also reducing the risk of human error.

Initially, a trial dataset of large and bright sources was established. This was defined as those sources whose size was greater than 60 arcsec and with a flux greater than 30 mJy. The modifications applied to the base code, described in detail in Chapter 3, increased the initial ridgeline drawing success rate from 78% to 96%. These modifications included the removal of extraneous emission and non-related source components, reduction of the image size, ability to navigate gaps in source emission, and careful selection of an initial starting point. The latter was needed since the starting point was no longer required to be associated with the host galaxy, which, unlike for the trial sample, would be unknown for future datasets.
From here, a likelihood ratio was calculated, and its application was discussed in Chapter 4. The likelihood ratio was chosen to maintain a similar method to that which was already in place, allowing for easier integration into the current pipeline, and to allow for a certain amount of control over the input parameters. I found that the most successful likelihood ratio uses a combination of the separation probability distribution functions of the centroid with the ridgeline distances (see Section 4.2.4). Here, the geometric mean of both functions was taken and used in the likelihood ratio. This method succeeded in correctly identifying 98.0% of the optical hosts for all sources \( > 10 \text{ mJy} \) and \( > 15 \text{ arcsecs} \) (which had a ridgeline drawn on them) in the DR1 sample. Included in this is the large and bright sample where 96% of the hosts were identified. For the fainter and smaller sources (10 to 30 mJy and 15 to 60 arcsec), because of the smaller sky area encompassing the source, there were fewer possible optical counterparts present, accounting for the higher outcome of 99% correctly identified sources. As discussed in detail in Chapter 6, there is still work to be done to improve the ridgeline drawing process of RL-XID for sources that are ‘too zoomed in’ and ‘blends’, and this process still relies on the sources being correctly associated beforehand.

As discussed in Section 4.1 the potential of ridgelines as part of an automated method for morphological classification was explored. In this section, the use of ridgelines to draw surface brightness profiles was investigated. These are representations of the flux density along the ridgeline and can be graphed to show where the areas of peak brightness have occurred. By investigating the location of the ‘peaks’ and ‘dips’ along these profiles it was possible to demonstrate that the surface brightness profiles can be well matched to LoMorph’s automatic morphological classifications (Mingo et al. 2019). The profiles classed as ‘dips’ with minimums values in a central location equate to the edge brightened FRIIs, and those classed as ‘peaks’, with a central maximum value are FRIs. Ridgelines have the potential to aid with automated techniques, and this can be developed further to enable more sophisticated classifications.

Chapter 5 focuses on the exploration of the properties of a population of low luminosity FRIIs (FRII-lows) discovered in LoTSS DR1 by Mingo et al. (2019). A follow up sample of 19 LoTSS-selected sources were observed with the VLA, and the observation datasets from the L band, A and B configurations, were processed as described in Chapter 2. These high frequency (1.5 GHz) and higher resolution (1.3 arcsec) images are used for comparison with a sample of
high luminosity FRIIs (FRII-highs). I identified a distinction in morphology between the FRII-highs and -lows where 92% of the FRII-lows contain compact features compared to 60% of the FRII-highs. There is a higher prevalence of cores in the FRII-lows, of 47%, compared to no cores identified in the FRII-highs. 60% of FRII-highs were found to have hotspots, compared to only 26% of FRII-lows. There is a possibility of jet features in 11% of the FRII-lows. However, one of these could be due to the high dynamic range of image ILTJ115011.27. The features could also mean that the source dynamics are more FRI-like, which was not evident in the lower frequency images.

The integrated spectral indices were measured between LoTSS and the VLA, $\alpha_{1500}^{150}$, and span the range of ~0.6 to 1.0 in cases where they are not lower limits. This is typical for active radio galaxies, and similar to the results found by Mingo et al. (2019) for their spectral indices with NVSS. For the six calculated as lower limits they all have values of $\alpha_{1500}^{150} > 1.1$.

Within this sample I identified six (32%) new remnant candidates and three (16%) new restarting candidates. Shabala et al. (2020) state that if > 10% of the population are genuine restarters this implies that an appreciable fraction of these sources are short-lived and/or low-powered. This aligns with the suggestion of Mingo et al. (2019) which is that the FRII-low population contains a mix of low-powered sources in low mass galaxies, able to maintain the FRII-like morphology, and older, fading sources.

There are many avenues for further exploration of this work involving both RL-X10 and the FRII-low population. As discussed in Section 6.1.1, RL-X10 is already being implemented on LoTSS DR2 with promising results. There are a few areas that the implementation of this can be improved. These include the formalisation of its completeness and reliability and exploring the optimal threshold for the likelihood ratio. Along with these, strategies need to be considered for sources which are 'too zoomed in' and 'blends'. Moving on from LoTSS DR2 is the implementation of the automated pipeline reducing some of the need for LGZ. Again, the same level of careful validation of the outputs needs to be considered as LoTSS DR2.

One of the specifications I wanted to ensure was met by RL-X10 was that of adaptability, the capacity for it to be used by other instruments and/or surveys, or easily adjustable should the requirements from LOFAR change. This has started to be explored in Section 6.1.3 with a data set from MIGHTEE, producing ridgelines on a sample of non-LOFAR data. The main issue which arose was the
lack of association for the larger sources. However, RL-XID was able to successfully produce ridgelines on single-component extended radio sources.

Chapter 6 also discusses furthering my work with the FRII-low population. This could be done through using the VLASS single-epoch images, or the software program BRATS (Harwood et al. 2013). Both of these will obtain better and more detailed spectral index information. This will improve the conclusions on the number of remnant and restarters candidates in the sample. In addition to this, the possible candidates already selected can be studied in detail. By creating spectral ageing maps or using the LOFAR international baselines to create high resolution images it would be possible to focus on the central (double-double) regions and confirm the restarting nature of the sources.

Finally, all aspects on my work can be brought together into one project: the search for a larger sample of FRII-lows in the full LoTSS DR2 catalogue. To do this would require LoMorph for the initial classification, followed by the identification of host galaxies using RL-XID. Once such a sample is identified, the LOFAR international baselines will provide high resolution images for morphological comparisons, and spectral index investigations. This would allow for a large sample of extended radio galaxies to be explored, and improve our knowledge for building galaxy population models, and understanding their evolution.

"Go then, there are other worlds than these."

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Jake Chambers,
Stephen King, The Dark Tower: The Gunslinger
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