Galaxy-scale jets with new extragalactic radio surveys

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Abstract

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Doctor of Philosophy

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by Brendan Webster

The effects of feedback from high luminosity radio-loud AGN have been extensively re-
searched, but feedback from physically small, low-luminosity radio-loud AGN is less well
understood. The advent of high sensitivity, high angular resolution, large field of view
telescopes such as LOFAR is now allowing wide-area studies of such faint sources for the
first time. Within this thesis I use data from the first release of the LOFAR Two Metre
Sky Survey (LoTSS) to report on my discovery of a population of 195 low luminosity radio
galaxies where the total extent of the radio emission is no larger than 80 kpc. These ob-
jects, which I term galaxy-scale jets (GSJ), are small enough to be directly influencing the
evolution of the host on galaxy scales. Combining the LoTSS data with new observations
taken with the Karl G. Jansky Very Large Array and the XMM-Newton telescope I report
upon the host and radio properties of the sample, finding that GSJ exhibit a mix of FRI
and FRII morphologies with host properties that are typical of those found in larger radio
galaxies showing that they are ordinary AGN observed at a stage in their life shortly after
the radio emission has expanded beyond the central regions of the host. I find that GSJ
generally inhabit sparse environments and are primarily young sources that are expanding
fast enough to drive shocks. Even ignoring shocks, which I do not detect for any of my
sample, I find that approximately half of my GSJ have internal radio lobe energy within
an order of magnitude of the ISM energy. For one source studied at X-ray wavelengths I
find the radio lobes have a significant proton content suggesting high levels of entrainment.
I conclude that GSJ are energetically capable of affecting the evolution of the host.
Acknowledgements

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SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, the Chilean Participation Group, the French Participation Group, Harvard-Smithsonian Centre for Astrophysics,
Instituto de Astrofísica de Canarias, The Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU) / University of Tokyo, the Korean Participation Group, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional / MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University.

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>3CRR</td>
<td>Third Cambridge radio catalogue (second revision)</td>
</tr>
<tr>
<td>ADAF</td>
<td>Advection-Dominated Accretion Flow</td>
</tr>
<tr>
<td>ADS</td>
<td>Astrophysics Data System</td>
</tr>
<tr>
<td>AGN</td>
<td>Active Galactic Nucleus / Active Galactic Nuclei</td>
</tr>
<tr>
<td>ALMA</td>
<td>Atacama Large Millimeter/sub-millimeter Array</td>
</tr>
<tr>
<td>AS</td>
<td>Automatic Sample</td>
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<tr>
<td>BCG</td>
<td>Brightest Cluster Galaxy</td>
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<tr>
<td>BLR</td>
<td>Broad Line Region</td>
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<tr>
<td>BLRG</td>
<td>Broad Line Radio Galaxy</td>
</tr>
<tr>
<td>BPT</td>
<td>Baldwin, Phillips and Telervich (diagram)</td>
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<tr>
<td>BRATS</td>
<td>Broadband Radio Astronomy Tools</td>
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<tr>
<td>CASA</td>
<td>Common Astronomy Software Applications</td>
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<tr>
<td>CCD</td>
<td>Charge-Coupled Device</td>
</tr>
<tr>
<td>CCF</td>
<td>Current Calibration Files (XMM)</td>
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<tr>
<td>CDM</td>
<td>Cold Dark Matter</td>
</tr>
<tr>
<td>CIAO</td>
<td>Chandra Interactive Analysis Operations</td>
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<tr>
<td>CORALZ</td>
<td>Compact Radio sources At Low Redshift (radio galaxy sample)</td>
</tr>
<tr>
<td>CSO</td>
<td>Compact Symmetric Object</td>
</tr>
<tr>
<td>CSS</td>
<td>Compact Steep Spectrum</td>
</tr>
<tr>
<td>CXC</td>
<td>Chandra X-ray Center</td>
</tr>
<tr>
<td>DR</td>
<td>Data Release (of a catalogue)</td>
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<tr>
<td>DRAGN</td>
<td>Double Radio Source Active Galactic Nucleus</td>
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<tr>
<td>EPIC</td>
<td>European Photon Imaging Cameras</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ESAC</td>
<td>European Space Astronomy Centre</td>
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<tr>
<td>FFA</td>
<td>Free Free Absorption</td>
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<tr>
<td>FIRST</td>
<td>Faint Images of the Radio Sky at Twenty centimeters</td>
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<tr>
<td>FITS</td>
<td>Flexible Image Transport System</td>
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<tr>
<td>FPBHA</td>
<td>Fundamental Plane of Black Hole Activity</td>
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<tr>
<td>FR</td>
<td>Fanaroff &amp; Riley radio source morphological classification</td>
</tr>
<tr>
<td>FSRQ</td>
<td>Flat Spectrum Radio Quasar</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>GPS</td>
<td>Gigahertz Peaked Spectrum</td>
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<tr>
<td>GSJ</td>
<td>Galaxy Scale Jet</td>
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<tr>
<td>GTI</td>
<td>Good Time Intervals</td>
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<tr>
<td>H-ATLAS</td>
<td>Herschel-ATLAS</td>
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<tr>
<td>HBA</td>
<td>High Band Antenna</td>
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<tr>
<td>HEASARC</td>
<td>High Energy Astrophysics Science Archive Research Center</td>
</tr>
<tr>
<td>HEASOFT</td>
<td>High Energy Astrophysics SOFTware</td>
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<tr>
<td>HERG</td>
<td>High Excitation Radio Galaxy</td>
</tr>
<tr>
<td>HETDEX</td>
<td>Hobby-Eberly Telescope Dark Energy Experiment</td>
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<tr>
<td>HEW</td>
<td>Half Equivalent Width</td>
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<tr>
<td>ICM</td>
<td>IntraCluster Medium</td>
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<tr>
<td>IGM</td>
<td>IntraGroup Medium</td>
</tr>
<tr>
<td>ILT</td>
<td>International LOFAR Telescope</td>
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<tr>
<td>ISM</td>
<td>InterStellar Medium</td>
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<td>JP</td>
<td>Jaffe-Parole (spectral ageing)</td>
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<td>KP</td>
<td>Kardashev-Pacholczyk (spectral ageing)</td>
</tr>
<tr>
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<td>Low Band Antenna</td>
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<td>LeMMINGs</td>
<td>Legacy eMerlin Multi-band Imaging of Nearby Galaxies Survey</td>
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<td>Low Excitation Radio Galaxy</td>
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<td>LINER</td>
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<tr>
<td>LLAGN</td>
<td>Low Luminosity Active Galactic Nuclei</td>
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<td>LLC</td>
<td>Low Luminosity Compact (radio galaxies)</td>
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<tr>
<td>LOFAR</td>
<td>LOw Frequency ARray</td>
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<td>LoTSS</td>
<td>LOFAR Two-metre Sky Survey</td>
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<td>LPC</td>
<td>Low Power Compact (radio galaxies)</td>
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<td>MCMC</td>
<td>Markov Chain Monte Carlo</td>
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<td>MOS</td>
<td>Metal Oxide Semiconductor (EPIC-MOS)</td>
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<td>MPA</td>
<td>Max Planck Institute for Astrophysics</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NFW</td>
<td>Navarro, Frenk and White (profile)</td>
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<td>New General Catalogue (of Nebulae and Clusters of stars)</td>
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<td>Narrow Line Region</td>
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<td>Narrow Line Radio Galaxy</td>
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<td>OOT</td>
<td>Out Of Time</td>
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<td>PN</td>
<td>P-type/N-type semiconductor (EPIC-pn)</td>
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<td>Pan-STARRS1 survey</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<td>PSF</td>
<td>Point Spread Function</td>
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<tr>
<td>PYBDSF</td>
<td>Python Blob Detector and Source Finder</td>
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<tr>
<td>RFI</td>
<td>Radio Frequency Interference</td>
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<td>RGS</td>
<td>Reflection Grating Spectrometer</td>
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<td>Radio Loud AGN</td>
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<td>Radio Loud Quasar</td>
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<td>Root Mean Square</td>
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<td>Radio Quiet AGN</td>
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<td>Radio Quiet Quasar</td>
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<td>Science Analysis System</td>
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<td>SDSS</td>
<td>Sloan Digital Sky Survey</td>
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<td>SFR</td>
<td>Star Formation Rate</td>
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<tr>
<td>SIMBAD</td>
<td>Set of Identifications, Measurements and Bibliography for Astronomical Data</td>
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<tr>
<td>SKA</td>
<td>Square Kilometre Array</td>
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<td>SMBH</td>
<td>SuperMassive Black Hole</td>
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<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<td>SQL</td>
<td>Structured Query Language</td>
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<td>SSA</td>
<td>Synchrotron Self-Absorption</td>
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<td>SSD</td>
<td>Shakura Sunyaev Disc</td>
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<td>Science and Technology Facilities Council</td>
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<td>Total Electron Content</td>
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<td>Tools for Operations on Catalogues and Tables</td>
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<td>TS</td>
<td>Total Sample</td>
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<td>ULIRG</td>
<td>Ultra-Luminous InfraRed Galaxy</td>
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<tr>
<td>UV</td>
<td>Ultraviolet (radiation)</td>
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<td>VLA</td>
<td>Karl G. Jansky Very Large Array</td>
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<td>VLBI</td>
<td>Very Long Baseline Interferometry</td>
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<td>VS</td>
<td>Visual Sample</td>
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<tr>
<td>WEAVE</td>
<td>William Herschel telescope Enhanced Area Velocity Explorer</td>
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<td>WENSS</td>
<td>Westerbork Northern Sky Survey</td>
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<td>WHAN</td>
<td>Width of the H Alpha and Nitrogen lines (diagram)</td>
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<td>WHT</td>
<td>William Herschel Telescope</td>
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<td>WISE</td>
<td>Wide-field Infrared Survey Explorer</td>
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<td>XMM-Newton</td>
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<td>XSPEC</td>
<td>X-ray SPECtral Fitting Package</td>
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Chapter 1

Introduction

Active galaxies can be defined as galaxies displaying some form of unusual activity emanating from their core. Despite only a minority of galaxies being classed as active, they are both ubiquitous and are believed to play a key role in shaping galactic evolution over cosmic timescales (Somerville & Davé, 2015; Naab & Ostriker, 2017). All active galaxies are fuelled by a central supermassive black hole (SMBH) accreting matter from their surroundings resulting in what is termed an active galactic nucleus (AGN).

This thesis is concerned with the sub-class of active galaxies called radio galaxies where the accretion process results in two radio-emitting jets being produced that carry energy away from the host. In particular, this thesis focuses on radio galaxies producing physically small jets up to a few tens of kpc in size, and the direct effect these jets may be having upon the host galaxy’s evolution. Defined fully in Chapter 4, the small-scale and potential galaxy-wide influence of these jets means that throughout this thesis I refer to them as galaxy scale jets (GSJ).

Within this chapter, Section 1.1 gives an overview of the various components of an AGN and explains why the study of AGN is a multi-wavelength discipline. Section 1.2 then describes the key terminology used within this thesis to describe active galaxies. As the name implies radio galaxies are most easily detected at radio frequencies; Section 1.3 therefore contains a description of the mechanism by which this radio emission is produced: the synchrotron process. Section 1.4 describes the bremsstrahlung emission coming from the regions into which radio galaxies propagate. Finally, Section 1.5 describes the mechanism by which radio jets can produce shocks in their environment along with an overview of the importance of these shocks to galactic evolution.

1.1 AGN Components

The traditional view of an AGN, which Heckman & Best (2014) describe as a radiative-mode AGN (see Figure 1.1), has the central SMBH gradually accreting material from a surrounding, cool, geometrically thin accretion disc. In these discs accretion occurs at \(~ 1\) per cent of the Eddington limit (also known as the Eddington luminosity) which is defined as the accretion rate at which the inward pull of gravity is equal to the outward radiation pressure. These discs are radiatively efficient, radiating as a thermal body at optical and ultraviolet wavelengths. The disc is itself immersed in an optically thin corona
which up-scatters disc-photons to X-ray energies. Inevitably some of these X-ray photons strike the accretion disc resulting in a reflection spectrum that is also observed in X-rays. Surrounding the disc and corona at distances between a few light months to a few hundred light years is a dusty obscuring structure, traditionally assumed to have a torus shape. This structure absorbs photons from the central regions of the AGN re-emitting its energy as thermal infrared radiation. The name for this type of AGN comes from the fact that the majority of energy emitted is in the form of radiation.

In some radiative-mode AGN, believed to be those with the most massive SMBHs, the accretion process can also result in two radio-emitting jets. Along with the jet-mode AGN (described below), these sources are classed as radio-loud. However, the majority of radiative-mode AGN do not produce radio jets and are described as radio-quiet.

![Figure 1.1: The central components of both radiative-mode and jet-mode AGN. Figure reproduced from Heckman & Best (2014).](image)

Radiative-mode AGN produce both broad and narrow emission lines so that they are also referred to as being ‘high-excitation’. The broad emission lines emanate from the broad line region (BLR) which is a region of relatively dense gas clouds located light-days to light years from the SMBH between the accretion disc and the dusty obscuring structure. The velocity dispersion of this region is several thousands of km s$^{-1}$ resulting in Doppler broadening of the emission lines giving the region its name.

The narrow emission lines come from the relative low-density gas clouds of the narrow line region (NLR) which is located a few hundred to a few thousand light years from the SMBH, beyond the dusty obscuring structure. The narrow line region has a velocity dispersion of a few hundred km s$^{-1}$ and is situated far enough away from the core so that, unlike the BLR, it is always visible irrespective of the host’s orientation. Differences in orientation are reflected in some of the different classifications of AGN (see Section 1.2.2).

Whilst some radiative-mode AGN can produce jets, the majority of radio galaxies are
believed to harbour a different type of AGN which Heckman & Best (2014) refer to as jet-mode. For this type of AGN the majority of the energy output is in the jet’s kinetic energy rather than a radiatively efficient core. As illustrated in Figure 1.1, the thin accretion disc in this type of AGN is believed to be either absent or truncated and instead the innermost accretion flow is best described by a hot, thick region with little or no emissions and inflow times that are shorter than the radiative cooling time so that little energy is released in the form of radiation. This type of AGN has very low accretion rates, typically $\lesssim 0.1$ per cent the Eddington limit. There is evidence that the jets in these objects are powered by the low accretion rates (Mingo et al., 2014), though a significant contribution from the SMBH’s spin cannot currently be ruled out (Fanidakis et al., 2011).

The emission lines seen in jet-mode AGN are typically far weaker (or even entirely absent) compared to the emission lines seen in radiative-mode AGN. This has led to the suggestion (illustrated in Figure 1.1) that jet-mode AGN do not have a BLR, only a weak NLR and no heavily obscuring structure. Evidence for this has been found in several infrared studies where no re-radiation of nuclear emission by the torus, as is seen in radiative-mode AGN, has been found (e.g. Whysong & Antonucci, 2004; van der Wolk et al., 2010). Similar results have been found in the X-ray regime where no evidence for heavily obscured nuclear emission have been found (Hardcastle et al., 2006, 2009) indicating no heavily obscuring structure is present. The lack of emission lines means ‘jet-mode’ AGN are sometimes also referred to as ‘low-excitation’. However, the two terms may not be synonymous as a recent study of ten low-excitation, FRI sources, revealed that four of them had infrared emission consistent with the presence of some form of obscuring structure with one of the four believed to have a clumpy torus like those typically associated with radiative-mode AGN (Gleisinger et al., 2020).

1.2 Terminology

The plethora of terms commonly used to identify and describe AGN can be overwhelming. Below is a brief overview of the terms used within this thesis when discussing AGN in general and radio galaxies in particular.

1.2.1 Morphological Classifications

Fanaroff & Riley first classified radio-loud galaxies in 1974 (Fanaroff & Riley, 1974). Those sources where the distance between the two brightest radio features was less than half of the total radio extent were called class I, and those where the distance was greater than half were called class II. These classes are now usually referred to as FRI and FRII respectively. Examples of the two classifications are shown in Figure 1.2 whilst Figure 1.3 shows the relative locations of all the galaxy classifications discussed in this section on a power-linear size plot. Fanaroff & Riley also found that FRII sources have a luminosity above, and FRI sources below, $L_{178\text{MHz}} \sim 10^{26}\text{W Hz}^{-1}$ ($L_{1.4\text{GHz}} \sim 10^{25}\text{W Hz}^{-1}$). Later studies showed that the break luminosity between FRI and FRII type morphologies increases
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Figure 1.2: Left: Galaxy 3C31, a typical FRI type galaxy Right: Galaxy 3C98, a typical FRII type galaxy. Figures created by M. Hardcastle and reproduced under the Creative Commons BY-SA 3.0 licence (https://creativecommons.org/licenses/by-sa/3.0/deed.en).

proportionally with the host galaxy luminosity (Ledlow & Owen, 1996). Recently, low-frequency studies have shown that whilst few FRI sources are found above this break, there is a population of low luminosity FRII sources found below this break (Mingo et al., 2019).

FRI jets are believed to be emitted at relativistic speeds, decelerating rapidly as they interact with the host’s halo, entraining material and ending in either a lobe or a plume. Specifically, those FRIs where the majority of the lobe is beyond the end of the collimated jet are ‘plumed’ whilst those where the majority of the lobe is between the start and end of the collimated jet are ‘bridged’. In contrast FRII jets remain relativistic for far larger distances, in some cases several Mpc, until they are suddenly terminated in regions known as hot spots (Heckman & Best, 2014). Material then leaks out from the hot spots forming the lobes. There is also a strong overlap with the radiative-mode/jet-mode classification with most FRII sources generating strong emission lines and being classed as radiative-mode (though there is a subset with weak or no emission lines). Equally most FRI sources are classed as jet-mode AGN with no emission lines (Best et al., 2005b).

The physically smallest classifications of Radio Galaxies are the Compact Symmetric Objects (CSO), Gigahertz Peak Spectrum (GPS) and Compact Steep Spectrum Sources (CSS). CSOs are physically the smallest of these compact objects with sizes less than a few hundred pc, while GPS sources are typically smaller than about 1 kpc with a peak in the radio spectrum between ~1 - 5 GHz and CSS sources are between 1 and 20 kpc with a peak in the radio spectrum below 500 MHz (for a recent review of these sources see O’Dea & Saikia, 2021).

More recently a new class of FR0 object has been identified where the central AGN
is radio-loud, yet there is no resolved (or only slightly resolved) extended emission (Baldi et al., 2015). These sources are far more numerous than the traditional FRI/FRII sources and therefore comprise the majority of radio-loud AGN in the local Universe. These FR0 sources have similar properties to FRI sources with the same compact core only without the extended radio emission (Baldi & Capetti, 2009).

### 1.2.2 Host Classifications

Whilst the association of emission lines with radio galaxies dates back to Hine & Longair (1979), it is only recently that the significance of these lines has been understood. As mentioned in Section 1.1, the strong, broad emission lines come from the BLR whilst the narrow and forbidden lines come from the NLR. Depending upon the relative strengths of the emission lines it is possible to determine whether a radio galaxy contains a radiative-mode host, known as a high excitation radio galaxy (HERG), or whether it contains a jet-mode host, known as a low excitation radio galaxy (LERG) (Heckman & Best, 2014).

Although there is a strong overlap with the FRI/FRII classification with most FRI sources being LERGs and most FRII sources being HERGs, the two classification are not synonymous (though see Tadhunter, 2016a). Furthermore, some jet-mode AGN produce only very weak, small-scale radio emission. These objects are generally classed as low ionisation nuclear emission regions (LINERs) rather than LERGs (Heckman, 1980).

Radiative-mode AGN can also be classed as either radio-loud or radio-quiet, typically depending upon the ratio of observed optical to radio luminosities (e.g. Kellermann et al., 2016) with the Seyfert class of galaxy comprising the radio-quiet, radiative-mode AGN. Radio Quiet Quasars (RQQ) are highly luminous, very distant versions of Seyfert galaxies.
Unfortunately, contamination from both the host galaxies’ stars and dust obscuration can affect this method. Further, because radio-loudness is defined as a ratio, optically luminous sources can still have significant radio emission yet be classed as radio quiet. For example, some sources traditionally classed as radio-quiet and hosting radiative-mode AGN have been found to produce small radio jets up to 25 kpc in size (Jarvis et al., 2019). As a result, feedback from radio jets may still be important in objects normally classed as radio-quiet.

For radiative-mode AGN the orientation of the host galaxy may result in the bright core and BLR being hidden from view by the surrounding dusty obscuring structure, so that only the NLR is visible. Those AGN where there is a direct line of sight to the central region are called type 1 and those where the central region is obscured are called type 2. Type 1 radio galaxies are occasionally called broad line radio galaxies (BLRG) whilst type 2 radio galaxies are similarly sometimes called narrow-line radio galaxies (NLRG). Equally, some radio galaxies are oriented with their jets pointing straight towards us. These are known as blazars. Blazars can be further sub-divided into sources with a jet-mode AGN, known as BL Lac objects, or those with a radiative-mode AGN, known as flat spectrum radio quasars (FSRQ). Of course, the extent to which the core is hidden from view depends upon the covering fraction of the sky as seen from the SMBH which raises the question of what causes the covering fraction to vary and whether it might be linked to accretion mode. For jet-mode AGN the orientation does not affect the host classification except in the extreme case of BL Lac objects.

1.3 Synchrotron Radiation

The radio emission coming from radio galaxies originates in the synchrotron process. The explanation of synchrotron radiation below adopts the same structure as Condon & Ransom (2016) to which readers should refer for more details (N.B. I am presenting the SI versions of the CGS formulae described by Condon & Ransom). Any electrically charged particle that is subject to some form of acceleration will emit radiation. Larmor’s equation (Equation 1.1) describes the total power emitted by a non-relativistic charged particle subject to some form of acceleration as:

$$P = \frac{1}{6\pi\varepsilon_0} \frac{q^2a^2}{c^3}$$  \hspace{1cm} (1.1)

where $q$ is the charge of the particle, $a$ is the acceleration and $c$ is the speed of light in a vacuum. As can be seen, the power radiated is proportional to the acceleration squared.

Since most astrophysical sources are accelerated by electromagnetic forces the acceleration tends to be proportional to charge/mass. As a result, electrons produce $(m_p/m_e)^2 \sim 4 \times 10^6$ more synchrotron radiation than protons. This is why protons are treated as being essentially non-radiating particles. However, this power is not emitted isotropically. It
turns out that the power radiated at any given angle $\theta$ (relative to the direction of acceleration) is proportional to $\sin^2 \theta$ so that when viewed along the line of acceleration no power is transmitted whilst perpendicular to the line of acceleration the maximum amount of power is seen.

Since Larmor’s equation is non-relativistic, it is only valid when the velocity $v \ll c$. In order to use Larmor’s equation in relativistic situations, such as those found in radio galaxies, it is necessary to first calculate the radiation produced in the particles own rest frame and then transform the results into the observer’s rest frame using the inverse Lorentz transformation rules. Performing this transformation gives the observed power of a relativistically moving electron as:

$$P = \frac{1}{6\pi\epsilon_0} \frac{e^2 a_\perp^2 \gamma^4}{c^5}$$  \hspace{1cm} (1.2)

where $a_\perp$ is the acceleration perpendicular to the particle’s velocity and $e$ is the charge of an electron.

Within radio galaxies the acceleration that gives rise to the observed synchrotron radiation is caused by the motion of the electrons relative to magnetic fields as given by the Lorentz force law $\vec{F} = q(\vec{v} \times \vec{B})$. In order to keep the electron in a circular orbit the angular gyration frequency, $\omega_G$, is:

$$\omega_G = \frac{eB}{m_e}$$  \hspace{1cm} (1.3)

However, since the particles are moving relativistically we must replace the rest mass with the relativistic mass giving the relativistic angular gyration frequency $\omega_B$:

$$\omega_B = \frac{eB}{\gamma m_e} = \frac{\omega_G}{\gamma}$$  \hspace{1cm} (1.4)

The observed perpendicular acceleration of the electron is therefore:

$$a_\perp = \omega_B v_\perp = \frac{eB}{\gamma m_e} v_\perp = \frac{eBv \sin \alpha}{\gamma m_e}$$  \hspace{1cm} (1.5)

where the pitch angle, $\alpha$, is the angle between the direction of the electron’s velocity and the direction of the magnetic field. Inserting this into equation 1.2 yields the power radiated by a single electron:

$$P = 2\sigma_T \beta^2 \gamma^2 cU_B \sin^2 \alpha$$  \hspace{1cm} (1.6)

where $\sigma_T = e^4/(6\pi\epsilon_0^2 m_e^2 c^4)$ is the Thomson cross-section and $U_B = B^2/2\mu_0$ is the magnetic energy density. As a result of the $\gamma^2$ term it can be seen that the power emitted by a single electron depends on the square of its kinetic energy.

Assuming astrophysical sources have relativistic electrons with an isotropic range of pitch angles, the average synchrotron power would be:

$$\langle P \rangle = 2\sigma_T \beta^2 \gamma^2 cU_B \langle \sin^2 \alpha \rangle = \frac{4}{3} \sigma_T \beta^2 \gamma^2 cU_B$$  \hspace{1cm} (1.7)
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In practice if $\gamma \gg 1$ then $\beta^2 = 1 - \gamma^{-2} \approx 1$ and can be ignored.

Whilst this power is being emitted continuously by the electron, relativistic beaming means that, in the observer’s rest frame, the power is beamed in the direction of travel. Further, because the electron is in a circular orbit due to the magnetic field, this emitted power is only seen for the short duration when the electron is moving towards the observer. As a result the observer actually sees a series of short pulses.

The observed power spectrum is the Fourier transform of this series of pulses. The resulting synchrotron power spectrum for a single electron is shown in Figure 1.4 where $x = \nu/\nu_c$, $F(x)$ is the function defining the shape of the power spectrum and $\nu_c$ is the critical frequency (i.e. the frequency at which power is maximised) which turns out to be:

$$\nu_c = \frac{3}{2} \frac{eB}{2\pi m_c} \gamma^2 \sin \alpha \propto E^2 B_\perp$$  \hspace{1cm} (1.8)

In other words, a single electron emits most of its power at a frequency that is proportional to its energy squared times by the perpendicular component of the magnetic field.

In real-life sources, such as radio galaxies, there are multiple synchrotron emitting electrons with a power-law energy distribution:

$$n(E)dE \propto E^{-\delta}dE$$  \hspace{1cm} (1.9)

where $\delta$, is called the injection index and $n(E)$ is the number density of electrons with energy in the range $E$ to $E + dE$. Making the simplifying assumption that each electron emits all of its average power at its critical frequency, the total power emitted over the frequency range $d\nu$ centred on the frequency $\nu$ is the average power emitted by the electrons.
within that range multiplied by the number of electrons in that range:

\[ P(\nu)d\nu = \langle P \rangle n(e)dE \]  

(1.10)

It can be shown that this becomes:

\[ P(\nu) \propto B^{(\delta+1)/2}\nu^{(1-\delta)/2} \]  

(1.11)

Thus, both the observed spectrum and the electron energy distribution are power laws. Defining the spectral index, \( \alpha \), as the negative of the slope of the power emitted so that \( P(\nu) \propto \nu^{-\alpha} \) it can be seen that the spectral index is related to the injection index by the equation:

\[ \alpha = \frac{\delta - 1}{2} \]  

(1.12)

It should be noted that there is no fixed convention on whether the spectral index should be quoted as either a positive or negative number. This leads to the alternative definition of the spectral index \( P(\nu) \propto \nu^\alpha \). However, this alternative definition is not used in this thesis.

### 1.3.1 Minimum Energy and Equipartition

As shown in Equation 1.7, the radio power emitted by a single electron depends on both the electron’s energy and the strength of the magnetic field. In order to estimate the total energy that must be output by a source to generate the observed spectra, it is common to assume either minimum or equipartition conditions for the particle and magnetic energy densities.

The energy density of electrons with energies between \( E_{\text{min}} \) and \( E_{\text{max}} \) is

\[ U_e = \int_{E_{\text{min}}}^{E_{\text{max}}} En(E)dE \]  

(1.13)

where \( n(E) \) is the number density of electrons with energies between \( E \) and \( E + dE \). From Equation 1.9 we know that \( n(E) = \kappa E^{-\delta} \) where \( \kappa \) is the constant of proportionality. Substituting this into the above equation gives:

\[ U_e = \kappa E^{2-\delta}\left|\frac{E_{\text{max}}}{E_{\text{min}}}\right| \]  

(1.14)

It was shown in Equation 1.8 that most power is emitted when \( \nu \propto E^2B \), hence the maximum and minimum energies are related to frequency according to:

\[ E_{\text{max}} \propto \left(\frac{\nu_{\text{max}}}{B}\right)^{1/2}; \ E_{\text{min}} \propto \left(\frac{\nu_{\text{min}}}{B}\right)^{1/2} \]  

(1.15)
Substituting these into Equation 1.14 gives:

\[ U_e \propto \kappa \left[ \left( \frac{\nu_{\text{max}}}{B} \right)^{(2-\delta)/2} - \left( \frac{\nu_{\text{min}}}{B} \right)^{(2-\delta)/2} \right] \]  

(1.16)

However, the luminosity of any given synchrotron source also depends upon the number density of electrons, and hence the constant of proportionality \( \kappa \), according to the formula:

\[ L \propto -\int_{E_{\text{min}}}^{E_{\text{max}}} (\frac{dE}{dt})n(E)dE \]  

(1.17)

It was shown in Equation 1.7 that the power emitted by a single electron is \((-dE/dt) \propto \gamma^2 U_B\), which is itself proportional to \(E^2 B^2\). Substituting both this and Equation 1.9 into the above formula gives:

\[ L \propto \kappa \int_{E_{\text{min}}}^{E_{\text{max}}} E^2 B^2 E^{-\delta} dE \]  

(1.18)

Solving this equation using the maximum and minimum energy limits in Equation 1.15 gives:

\[ L \propto \kappa B^2 \left[ \left( \frac{\nu_{\text{max}}}{B} \right)^{(3-\delta)/2} - \left( \frac{\nu_{\text{min}}}{B} \right)^{(3-\delta)/2} \right] \]  

(1.19)

Remembering that the luminosity in this equation is constant, this shows us that:

\[ \kappa \propto B^{-2} B^{(3-\delta)/2} = B^{-(\delta+1)/2} \]  

(1.20)

Inserting this formula for the constant of proportionality \( \kappa \) into Equation 1.16 and simplifying shows that the electron energy density scales as:

\[ U_e \propto B^{-3/2} \]  

(1.21)

In addition to the synchrotron-emitting electrons, protons and heavier ions also emit negligible amount of synchrotron energy so that the total energy in relativistic particles is \( U_E = (1 + \eta) U_e \) where \( \eta \) is the ion/electron energy ratio. However, it is still true that \( U_E \propto B^{-3/2} \). Combining this with the magnetic energy density, \( U_B \propto B^2 \), the total energy density is

\[ U = (1 + \eta)U_e + U_B = U_E + U_B \]  

(1.22)

A plot of the energy densities is given in Figure 1.5 with the lowest point in the solid total energy curve representing the minimum energy condition. Equipartition is the point at which the particle and magnetic energy are equal. Detailed calculations show that for minimum energy conditions, the particle energy density is \( 4/3 \) of the magnetic energy density. The closeness of these values mean equipartition and minimum energy estimates are always similar with equipartition values frequently assumed in practice. However, despite this common assumption it should be noted that it is unknown whether synchrotron sources are in equipartition or not (see Section 1.3.2).
1.3. Synchrotron Radiation

\[ U = U_B + U_E \]

\[ \text{Figure 1.5: For a source of given synchrotron luminosity, the corresponding particle and magnetic energy densities (} U_E \text{ and } U_B \text{ respectively) along with the total energy density, } U. \text{ Also shown are the magnetic fields strengths associated with minimum and equipartition energies, labelled } B_{\text{min}} \text{ and } B_{\text{eq}} \text{ respectively.} \]

1.3.2 Application to Radio Galaxies

Observations have shown radio galaxies at low redshift typically have an integrated spectral index of around 0.7 (Laing et al., 1983; Condon et al., 2002; Sabater et al., 2019), slightly steeper than the value of 0.6 found for supernovae (Green, 2009). However, this is an average and individual sources will vary. A relation between integrated spectral properties, size and redshift are expected on theoretical grounds, and have also been observed in large samples (de Gasperin et al., 2018; Tisanić et al., 2020). Also, core-dominated and compact sources are expected to have flatter spectral indices (below 0.5) due to the effects of synchrotron self-absorption and free-free absorption (O’Dea & Saikia, 2021).

It was noted in Section 1.3 that the power of emitted synchrotron radiation is proportional to \( E^2 \). As a result, the more energetic electrons lose energy to synchrotron radiation faster than lower energy electrons. It was also shown above that the critical frequency at which electrons emit most of their power is also proportional to \( E^2 \) which is why when we look at older sources fewer high energy electrons are seen and why the critical frequency also increases causing the spectral index to steepen (e.g. Heesen et al., 2014) as illustrated in Figure 1.6. By measuring the emissivity at different frequencies and by comparing to models it is therefore possible to estimate the age of radio sources, often referred to as the spectral age. Though beyond the scope of this work, spectral ageing models also account for inverse Compton energy losses which are proportional to the electron energy squared and therefore also affects higher energy electrons more severely (e.g. Jaffe & Perola, 1973; Kardashev, 1962). This is also why low frequency surveys are less affected by synchrotron
ageing and are therefore able to detect large populations of radio galaxies increasing our ability to study the evolution and effects of these objects.

Spatially resolved spectral index maps of radio galaxies show the effects of ageing with the flattest spectral indices occurring closest to the acceleration sites, becoming gradually steeper further away (e.g. Myers & Spangler, 1985; Alexander & Leahy, 1987; Harwood et al., 2013). The cores of radio galaxies as well as any hotspots therefore have the flattest spectral indices. However, in these regions the density of electrons means that the spectral index can become inverted due to either free-free or synchrotron self-absorption if the electrons are sufficiently dense (Morganti et al., 1997; Hovatta et al., 2014). This is the source of the spectral turnover seen in the compact CSS/GPS sources (Section 1.2.1). In practice, real-world sources are likely to be a mix of compact and extended emission, so that spectral indices below a value (typically 0.5) are generally considered indicative of a compact core-dominated object.

As well as using spectral ageing, radio galaxy source ages can also be estimated by dividing the size of a source by its expansion speed, known as the dynamic age. The expansion speed can be found in a variety of ways including from X-ray measurements of any shock front (Croston et al., 2007, 2009, 2011), by considering lobe length asymmetries (Scheuer, 1995) or by assuming expansion at the local sound speed (Bîrzan et al., 2004, 2008). Unfortunately, the two methods often produce different results with spectral ages being up to an order of magnitude lower than dynamical ages (Harwood et al., 2015). These differences could be due to a combination of the equipartition magnetic field strengths used in spectral age models and mixing of old and young populations of electrons along the line of sight, both of which would cause spectral ages to be lower (Mahatma et al., 2020). The assumptions of constant expansion speeds and the large uncertainties in estimating expansion speeds could also be affecting dynamic age estimates. It is believed that spectral ages are more accurate for younger sources (Blundell & Rawlings, 2000).

It was shown in Section 1.3.2 that for any given luminosity, the particle and magnetic
1.3. Synchrotron Radiation

energy densities are degenerate. However, by measuring the radio luminosity and assuming either minimum or equipartition conditions it is possible to calculate the energy density. Combining this with the volume of the emitting region (typically estimated by assuming either a spherical or cylindrical emitting regions) gives the internal energy which for a relativistic plasma undergoing adiabatic expansion is equivalent to $3pV$. However, these estimates do not account for the work done in inflating the radio lobes and so the total energy supplied by the jet is equivalent to $4pV$ (e.g. Burzan et al., 2004; Croston et al., 2009). These estimates also do not account for the presence of any shocks and so the total energy output may be significantly higher (see Section 1.5).

Applying this technique, it has been found that even at equipartition, the energy requirements for large luminous galaxies such as Cyg A are enormous (values of the order $10^{54}$ J or more are not uncommon). The total energy required to account for the observed radio emission only increases the further away a source is from equipartition (Hardcastle & Croston, 2020).

For FRII sources, rather than relying on equipartition estimates of the magnetic field strength it is possible, using inverse Compton emission from the lobes to deduce their particle content and then, by combining this with the observed radio synchrotron emission, to derive the magnetic field strength. Using the largest number of sources studied to date, Ineson et al. (2017) found the average magnetic field strength is about 0.4 times the equipartition value. This confirmed the results of previous, smaller studies (e.g. Croston et al., 2005b; Kataoka & Stawarz, 2005). As a result, Ineson et al. (2017) find the internal energy within the lobes of FRII sources are typically greater than equipartition estimates by a factor of $\sim 2.4$.

However, for FRI sources, the thermal X-ray emission of the environment dominates over the inverse Compton emission from the lobes (Hardcastle & Croston, 2010) so that it is generally not possible to derive the particle content and hence the magnetic field strengths within the lobes. Instead, the internal pressures derived for FRIs using equipartition pressure estimates with no proton content are often found to be lower than the external pressure of the surrounding environment (Morganti et al., 1988; Dunn et al., 2005; Croston et al., 2018). This suggests either a substantial contribution from non-radiating particles or magnetic field strengths much stronger than equipartition values or a combination of the two (Croston et al., 2003). In either case, in the absence of a significant non-radiating population, FRIs have significant departures from equipartition conditions.

Whilst stronger magnetic fields in FRIs cannot be ruled out, they would require extremely high strengths of 1 - 4 mT, far stronger than the $\sim 1$ nT typically seen in FRIIs. Models also predict these fields would decrease with distance at a faster rate than would be required to maintain pressure balance (Croston & Hardcastle, 2014). This suggests a key role for entrainment of non-radiating particles from the local environment. Though there is significant scatter for individual sources, the true energy in the lobes of FRI galaxies, assuming equipartition magnetic field strengths, is about an order of magnitude greater than the equipartition energy estimate (Croston et al., 2008a, 2018).
This was the case for NGC 3801, a low power FRI GSJ found to be storing about \(10^{56}\) \(\text{erg}/10^{49}\) J, a factor of \(\sim 4 - 6\) times higher than the minimum energy estimate (Croston et al., 2007). The same study also showed that despite the relatively low-power radio jets, compared to the energy output of a supernova which is typically about \(10^{51}\) erg (\(10^{53}\) erg if neutrino energy is included, Janka et al. 2012), the energy requirements remain enormous.

Once both the total energy needed to create the observed lobe and the age of the source is known, it is possible to derive the average power of radio galaxies. As a result, power output of radio galaxies is known to extend over several orders of magnitude from \(\sim 10^{35}\) W for low-power galaxies such as NGC 3801 (Croston et al., 2007) to \(\sim 10^{39}\) W for higher power galaxies (Croston et al., 2018).

### 1.4 Bremsstrahlung Radiation

The environments into which the lobes of radio galaxies expand, either the intracluster (ICM) or intragroup medium (IGM), are characterised as non-relativistic optically thin plasma. This plasma emits continuum radiation via the bremsstrahlung emission process that can be observed at X-ray frequencies. In addition, thermal plasma also produces emission lines (Sarazin, 1986). In the case of radio galaxy environments, the most important to this thesis is the Fe L complex around 1 keV visible at X-ray frequencies, though there are also several smaller lines seen at energies below 2 keV due to oxygen, magnesium, silicone and sulphur. Whilst the models used to represent thermal plasmas in Section 3.4.3.7 do use these lines to produce accurate spectra from which I derive temperature estimates, I do not perform any detailed spectral analysis of radio galaxy environments within this thesis and so do not consider line emission processes any further. Therefore, within the remainder of this chapter I focus on the bremsstrahlung process followed by a description of how this emission can be used to deduce several properties about the environments into which radio galaxies expand.

Within clusters/groups of galaxies, and even within individual galaxies, the gas within the surrounding environment falls into the gravitational potential well, collides with other particles and becomes shock-heated. A larger gravitational potential well is therefore more likely to result in greater shocking heating and hence a hotter environment. These collisional interactions result in a hot thermal plasma.

Within this environment, free electrons that pass near an ionised atom are deflected by the ion’s electric field resulting in bremsstrahlung emission. The emissivity of an electron moving with velocity \(v\) through a plasma with ion density \(N\) is given by (Equation 6.39 in Longair, 2011):

\[
I(\nu) \propto N \frac{1}{v} \ln \left( \frac{b_{\text{max}}}{b_{\text{min}}} \right)
\]

(1.23)

where \(I(\nu)\) is the emissivity at frequency \(\nu\) and \(b_{\text{max}}\) and \(b_{\text{min}}\) are the maximum and
minimum interaction distances (the collision parameters). The emissivity has no dependence upon frequency so that for a hypothetical plasma where every electron had the same velocity, the spectrum below the cut-off frequency (described below) is flat.

The frequency at which this plasma would emit depends upon the duration of each pulse via the Fourier transform. Taking $b$ as the impact parameter, the duration of each pulse (the time when the electron is strongly affected by the ion) is $\tau = 2b/\gamma v$ (Figure 5.4 in Longair, 2011) corresponding to the frequency $\nu \approx 1/\tau = \gamma v/2b$. From this it can be seen that the cut-off frequency occurs when, to an order of magnitude, $b_{\text{max}} = \gamma v/2\nu_{\text{cutoff}}$. For larger values of $b$ the electron and ion do not interact strongly creating the exponential tail of the spectrum.

Since electrons are lighter and more easily accelerated, the relative speeds of the electron and ion, $v$, depend primarily upon the electron’s energy and hence its temperature. In the simplified case where all the electrons have the same velocity $v$, it is therefore possible to derive the plasma temperature directly from the spectrum.

Using the maximum interaction distance above and taking the positional uncertainty for an electron of velocity $v$ as the minimum interaction distance, then integrating over all frequencies gives the energy loss rate as:

$$-\frac{dE}{dt} \propto Nv$$

This shows that individual electrons lose energy at a rate proportional to the square root of their kinetic energy.

Unlike the ideal scenario described above, the electrons within the optically thin plasmas seen in the ICM/IGM have a range of velocities described by the Maxwell-Boltzmann distribution. These are described as thermal plasmas. To obtain the emissivity for a thermal plasma, Equation 1.23 must be integrated over both the collision parameters and the energy distribution of the electrons. This results in the spectral emissivity for a plasma of:

$$I(\nu) \propto NN_e \left( \frac{m_e}{kT} \right)^{1/2} g(\nu, T)$$

where $N_e$ is the electron number density and $g(\nu, T)$ is the Gaunt factor.

This shows that the luminosity of an optically thin thermal plasma is related to its density (and hence its mass) with a weaker dependence on its temperature. There is also a weak dependence on frequency via the Gaunt factor, which varies slowly with frequency. Therefore, by modelling real-world observed X-ray spectra as coming from an optically thin thermal plasma, it is possible to estimate the temperature. In practice these estimates also rely on observed emission line strengths.

As above it is possible to calculate the energy loss rate for a thermal plasma by integrating Equation 1.25 over all the frequencies, giving:

$$-\left( \frac{dE}{dt} \right) \propto T^{1/2} NN_e \bar{g}$$

(1.26)
where \( \bar{g} \) is the frequency averaged Gaunt factor, which is often quoted as being 1.2 (Longair, 2011), though detailed calculations show the true value lies between 1.1 and 1.5.

### 1.4.1 Application to Radio Galaxy Environments

Unlike the idealised plasma described in the previous section, neither the temperature nor density of the ICM/IGM is uniform with both decreasing with distance from the centre. Whilst some studies have performed a detailed analysis of these temperature gradients (e.g. Russell et al., 2018; Simionescu et al., 2008), data quality means this is not always possible and so the environmental temperature is often quoted as a single characteristic value. This is the temperature an isothermal plasma would have in order to produce the observed spectral profile.

Using the principles described above to model the observed X-ray spectrum of the ICM/IGM as a thermal plasma (see Section 3.4.3.7 for details), it is possible to estimate the plasma’s temperature. Applying this technique, the hot gas in clusters of galaxies are typically found to have temperatures between \( 10^7 \) and \( 10^8 \) K (about 1 and 10 keV), whilst groups of galaxies tend to have temperatures between \( 10^6 \) and \( 10^7 \) K (about 0.5 and 2 keV).

Since \( N \propto N_e \), Equation 1.26 shows that the luminosity of any given region is proportional to the plasma density squared along the line of sight. Assuming a spherically symmetric, isothermal environment it is therefore possible to use the observed surface brightness profile of a group/cluster to derive its density profile (see Section 3.4.4.2 for details).

Using the ideal gas law:

\[
P = \frac{\rho k T}{\mu m_p}
\]

(1.27)

where \( k \) is Boltzmann’s constant, \( T \) is temperature, \( \mu \) is the mean particle weight (0.6 for primordial abundances, Rosati et al. 2002) relative to the mass of a proton, \( m_p \), and combining with the plasma temperature, the density profile can be converted into a pressure profile.

Assuming that the environment is in hydrostatic equilibrium with the total enclosed (baryonic and dark) matter of the host allows the gravitational force to be equated with the outward pressure of the gas giving:

\[
\frac{dP}{dr} = -G \frac{M(<r)\rho(r)}{r^2}
\]

(1.28)

where \( P \) is the gas pressure, \( G \) is the gravitational constant, \( M(<r) \) is the total mass with the radius \( r \) and \( \rho(r) \) is the gas density at radius \( r \). Combining Equations 1.28 and 1.27 shows that the temperature of the surrounding environment is related to the total mass, the \( M-T \) relation.

The virial theorem relates the average gravitational potential energy and the average kinetic energy of any spherical group of particles in hydrostatic equilibrium. If \( R_\Delta \) is the
radius at which the average plasma density is $\Delta$ times the critical density of the universe, $\rho_c$, and $M_\Delta$ is the mass within this region then this relation tells us that the mass and temperature are related according to:

$$kT \propto \frac{M_\Delta}{R_\Delta}$$  \hspace{1cm} (1.29)

Expressing $M_\Delta$ in terms of $R_\Delta$ gives $M_\Delta \propto \frac{4}{3} \pi R_\Delta^3$. Combining this with Equation 1.29 to eliminate $R_\Delta$ gives the $M$-$T$ relation (e.g. Gitti et al., 2012):

$$M \propto T^{3/2}$$  \hspace{1cm} (1.30)

Integrating Equation 1.26 over its volume gives the X-ray luminosity, $L_X$, of an optically thin plasma. Since integrating density over volume gives mass it follows that $L_X \propto MT^{1/2}$. Combining this with the result from the $M$-$T$ relation gives us the theoretical $L_X$-$T$ relation: (e.g. Arnaud & Evrard, 1999):

$$L_X \propto T^2$$  \hspace{1cm} (1.31)

In practice observations show a steeper relation indicating that some other processes must be involved. For example, Arnaud & Evrard (1999) find $L_X \propto T^{2.9}$. The cluster richness and whether or not it has a cool-core have all been shown to alter the $L_X$-$T$ relation (e.g. Stott et al., 2012; Pratt et al., 2009) with similar results found for groups (Bharadwaj et al., 2015).

### 1.5 Shocks

Shocks are created when a disturbance travels through a gas/plasma faster than the local speed of sound. In the context of radio galaxies this can occur when the radio lobes expand, displacing the hot gas in the surrounding environment. As a result, radio lobes are often visible as cavities in X-ray images. As material is swept up its density increases, resulting in a density contrast between the shocked and unshocked material. A strong shock has a density contrast of four whilst weak shocks have lower density contrasts.

In order for any object to expand and produce a shock the internal pressure must be greater than the external pressure. Almost all visible radio galaxies are overpressured since, if they were underpressured, they would collapse at the sound speed and quickly become invisible to us. However, radio galaxies do not have to be massively overpressured in order to expand.

At the shock front particles within the surrounding environment become compressed causing them to heat up and become a thermal source of X-rays emitting radiation via the bremsstrahlung process (Section 1.4). Both the Circinus galaxy (Mingo et al., 2012) and NGC 3801 (Croston et al., 2007) provide examples of this occurring in galaxy scale jets.
Figure 1.7: The south west lobe of Centaurus A. The red cocoon shape is the X-ray emission from the particles within the shocked shell created by the radio jets. Image from Croston et al. (2009).

Though the fluxes are normally too low to be significant, the particles accelerated by the shock front will also emit radiation via the synchrotron process (Section 1.3). However, if the shock front accelerates particles to sufficient speeds this can become the dominant emission process resulting in an observed power law profile. An example of this is occurring in Centaurus A (Figure 1.7) where the south west jet is about 10 kpc long and creates a shell around the lobe that is visible in X-rays (Croston et al., 2009).

Whilst both thermal and synchrotron processes are likely to be occurring simultaneously, Mingo et al. (2012) argue that in low power radio galaxies the thermal method is likely to be dominant as they typically lack the power to accelerate particles to X-ray emitting speeds.

The total energy injected into the radio lobes is often calculated using the formula \( E_{\text{cav}} = f_{\text{cav}} pV \) where \( p \) is the internal pressure, \( V \) is the lobe volume and \( f_{\text{cav}} \) is a value used to allow for the work done in inflating the lobes (Heckman & Best, 2014). It was mentioned in Section 1.3.2 that for a relativistic plasma undergoing adiabatic expansion most authors use a value of 4 for \( f_{\text{cav}} \). However, the presence of shocks invalidates the adiabatic assumption implying larger values for \( f_{\text{cav}} \).

When shocks are present, the total energy injected is the sum of the lobe’s internal energy plus the amount of energy within the shock (i.e. transferred to the environment). The energy within the shock is itself the sum of the thermal energy of the particles that form the shocked shell plus the kinetic energy of the shell as it moves outward into the surrounding environment. Using X-ray measurements, the shocked region can be modelled to estimate its temperature, density and hence pressure (Sections 1.4.1 and 3.4.3.7). Combining this information with the volume of the shocked region the total thermal energy can be calculated. By also measuring the temperature and pressure in the surrounding environment and comparing it with the pressure within the lobe, the speed of the shock can be found from which the kinetic energy of the shock front can be derived.
Since the pressure within the shock must be the same as the lobes, the pressure found for
the shocked region can be used as the internal lobe pressure. Combining this with the lobe
volume gives the $pV$ value as well the internal energy, which is $3pV$ for a relativistic plasma.
The $pV$ value can then be compared to the total energy. Adopting these techniques, a range
of values have been found for $f_{\text{cav}}$ with values up to 10 being quoted (Nusser et al., 2006)
showing that shock heating can be the dominant form of energy transfer.

1.6 Summary

Within this chapter I have presented an overview of the components that comprise a radio
galaxy. I have introduced the synchrotron and bremsstrahlung emission processes which,
when studying radio galaxies, are the processes primarily responsible for the emission
detected at radio and X-ray frequencies respectively. I have also described how these
observable emissions relate to the key radio galaxy properties discussed within this thesis.
In the following chapter I focus upon how radio galaxies can be identified based upon their
observable emission and what previously identified radio galaxies tell us about the sorts of
galaxies that host radio loud AGN and their interaction with their environment.
Chapter 2

AGN and their Hosts

It is generally believed that all galaxies harbour a central super-massive black hole (SMBH). When the SMBH accretes a sufficiently large amount of matter from its environment, the host can be described as an active galaxy with the central regions being the Active Galactic Nucleus (AGN). In practice all SMBHs are likely to interact with their host galaxies to some extent (e.g. in the case of Sgr A* see Bennewitz et al., 2019) and so several authors have defined criteria, some of which are described in Section 2.2, to determine when a galaxy can be described as ‘active’.

This chapter starts in Section 2.1 by outlining the importance of understanding the role of active galaxies in affecting galactic evolution before moving on, in Section 2.2, to describe various criteria used to identify active galaxies from existing survey data. Section 2.3 considers the typical properties of AGN host galaxies whilst Section 2.4 discusses how AGN feedback may affect those properties. Section 2.5 highlights the importance of understanding how small-scale radio jet activity can influence the evolution of the host. Section 2.6 concludes by identifying how I aim to expand upon this knowledge by summarising the main science questions this project was originally intended to address.

2.1 Galaxy Evolution

The current favoured model of galaxy evolution has baryonic matter falling into the gravitational wells of dark matter halos which, due to the conservation of angular momentum, form spiral galaxies (for example, see Benson, 2010; Mo et al., 1998; Dalcanton et al., 1997). These galaxies then interact (a) with each other: in the case of major mergers forming elliptical galaxies, and (b) with their environment: accreting the surrounding material and using it to form stars. According to this theory gas-rich major mergers are also responsible for creating starburst galaxies.

Initially these proto-galaxies were far smaller and less luminous than the galaxies they were to become. Over cosmic time these proto-galaxies grew, with SMBH growth and star formation rates of both elliptical galaxies and the bulges of spiral galaxies exhibiting a tight correlation (Shankar et al., 2009). Observations show that the growth rates for galaxies and their SMBHs have remained roughly proportional to each other, with both gradually increasing from cosmic dawn to a maximum at \( z \sim 2 \) followed by a sharp decline with both
growth rates decreasing by about an order of magnitude in absolute terms between $z=1$ and $z=0$.

Similar correlations are observed between black hole mass and other galactic properties. For example, between black hole mass and the velocity dispersion of the bulge (the $M_{\text{SMBH}}-\sigma$ relation), the mass of the bulge (the Magorrian relation), the luminosity of the bulge (the $M_{\text{SMBH}}-L_{\text{bulge}}$ relation) and the mass of the dark matter halo (for a detailed review see Kormendy & Ho, 2013). Collectively these relations imply a physical link between black hole growth and galactic evolution with most authors favouring some form of feedback between the two.

Furthermore, the high stellar and black hole growth rates seen at higher redshifts also mean that radio galaxies are more common at that time. The majority of today’s black hole and stellar mass was formed at $z\sim 2$, a period when late-type galaxies dominated so that spiral AGN hosts were more common at this time (Kaviraj et al., 2015b).

Those galaxies that are actively growing, increasing in both stellar and SMBH mass, as well as increasing in luminosity, form what is called the ‘main sequence’ of star-forming galaxies. These galaxies typically have small concentration indices ($C = R_{90}/R_{50}$) where $R_{50}$ is the radius containing 50 per cent of the light (i.e. late Hubble type), small stellar masses ($M_*$), low stellar surface mass densities ($\mu_* = 0.5M_*/(\pi R_{50}^2)$) and appear blue in colour. However, galactic growth cannot continue indefinitely and so there is also a population of galaxies where star formation (and presumably also SMBH) growth have either ceased or proceed at highly reduced rates. These galaxies are more massive than those on the main sequence and due to the lack of young stars they are also redder in colour so that they are sometimes referred to as being ‘red and dead’. These galaxies typically have high concentration indices (i.e. early Hubble type), large stellar masses and high stellar surface mass densities.

These two populations form what is often referred to as the blue cloud and red sequence, both groups are illustrated in Figure 2.1 for a sample of ‘local’ galaxies. Separating these two regions is a sparsely populated area known as the green valley. This bimodality in galaxy colours has been observed to persist out to a redshift of at least 3 (Whitaker et al., 2011).

Intuition would suggest that galaxies would continue to accrete matter from the environment, evolving along the blue cloud and growing in mass until there is nothing left to accrete at which point the galaxy would move on to the red sequence. However, the sparsely populated green valley is inconsistent with this gradual evolution, implying instead the onset of some quenching process that rapidly acts to shut down star formation moving galaxies from the blue cloud to the red sequence. Models show that galaxies stop accreting material and move on to the red sequence once they reach a critical mass (Heckman & Best, 2014). Coupled to this are observations that the efficiency with which galaxies convert cold gas into stars peaks at around $10^{12} M_\odot$ where about 20 per cent of baryons have been turned into stars. For both larger and smaller galaxies one or more processes are acting to lower the star formation efficiency. Since AGN on the blue cloud are more
2.1. Galaxy Evolution

likely to be radiative-mode and AGN in the red sequence are more likely to be jet-mode this suggests that whatever process is acting to quench star formation is also linked to a change in accretion mode (Heckman & Best, 2014).

Galaxies in the red sequence have typically exhausted their supply of cold gas so that, unlike galaxies on the blue cloud that have a plentiful supply of cold gas, the ultimate fuel source is believed to be the hot gas in the intragroup/intracluster medium (Heckman & Best, 2014). However, this is the same region into which radio jets are depositing their energy suggesting the existence of a feedback cycle (described further in Section 2.4). It is this feedback that is believed to be responsible for preventing large scale star formation from restarting in red sequence galaxies thereby preventing them from rejoining the blue cloud.

This overall picture finds support in theoretical models that, in order to reproduce the observed distribution and properties of galaxies, have consistently shown that some form of feedback process (sometimes called ‘maintenance-mode’) is necessary to supply energy to the environments of red sequence galaxies, restricting the rate at which the surrounding hot gas cools and is accreted back into the host (e.g. Somerville & Davé, 2015; Naab & Ostriker, 2017). This has the effect of preventing rapid star formation from restarting and maintaining the host galaxy on the red sequence. Some argue that supernovae (e.g. Dekel et al., 2019) and stellar winds (e.g. Murray et al., 2005b) are capable of driving gas from the centre of galaxies reducing star formation. In the case of late-type galaxies morphological quenching (e.g. Forbes et al., 2014), where the central spheroid restricts gas fragmentation within the disc, may also provide the feedback necessary to reduce star formation rates.

However, the prevailing view is that the above forms of feedback are more significant for lower mass galaxies and that for higher mass hosts (above $\sim 10^{12}M_\odot$) some form of
Active Galactic Nuclei (AGN) feedback is required (e.g. Somerville & Davé, 2015; Gutcke et al., 2017). For example, recent simulations such as Illustris (Vogelsberger et al., 2014) and EAGLE (Schaye et al., 2015) have included some form of AGN feedback in order to reproduce the observed distribution of galaxies.

In this thesis I am interested in the subset of AGN known as radio galaxies, an example of which is shown in Figure 2.2. For this class of galaxy, expanding radio lobes can frequently be seen to drive shocks, detectable at X-ray frequencies in to their surrounding environments (see Section 1.5). Using X-ray luminosities Birzan et al. (2004, 2008) showed that radio galaxies output sufficient energy to either completely offset, or at least significantly reduce the rate at which the surrounding hot gas cools, suggesting radio-jets play a key role in affecting the evolution of their hosts. This is also why maintenance-mode feedback is also frequently referred to as ‘jet-mode’ feedback. At the low redshifts studied in this thesis, radio galaxies are generally found in ellipticals (Matthews et al., 1964), though spirals can also host AGN, particularly on smaller scales (Kaviraj et al., 2015b). This supports the view that it is primarily AGN feedback that is restricting star formation rates in the most massive galaxies.

To date, due to their size and power, the majority of well-studied radio galaxies are huge with sizes between 100 and 1,000 kpc (e.g. Mullin et al., 2008). I am using the high angular resolution and sensitivity of the International LOFAR radio telescope to find much smaller jets with lengths up to about 40 kpc (i.e. a total, combined length of 80 kpc). The small size of these jets means that not only is the feedback loop happening over much shorter timescales than their larger counterparts, any shocks generated by the expanding lobes could be directly influencing the host (such as in NGC 3801 studied by Croston et al., 2007). The effects small radio galaxies can have upon the evolution of the host is discussed in more detail in Section 2.5.
2.2 Identifying AGN

Depending upon the data available there are several methods available to identify active galaxies. Several of these methods are used in Section 4.2 to identify the sample of GSJ used throughout this thesis.

2.2.1 Emission Line Methods

Type 1 radiative-mode AGN (see Section 1.2.2) are the easiest type of AGN to identify as our direct view of the BLR reveals the presence of strong, broad emission lines, providing determinative proof of an AGN (e.g. Hao et al., 2005). However, this is orientation dependent and so most authors prefer to use the narrow emission lines which are visible in both type 1 and type 2 radiative-mode AGN as well as many jet-mode AGN, although the strength of these lines depends upon a combination of the AGN strength and the covering factor. The active galaxies with the strongest emission lines contain radio-loud, radiative-mode AGN and are typically hosted by young, blue galaxies with high accretion rates situated in relatively poor environments (Lin et al., 2010).

The most common method of using narrow emission lines to identify AGN was developed by Baldwin, Phillips and Tefervich (Baldwin et al., 1981) and is commonly referred to as the BPT diagram (Figure 2.3). This method typically compares the [OIII]5007/H\(\beta\) pair of emission lines with the [NII]6584/H\(\alpha\) pair. However, both [OI]6300/H\(\alpha\) and [SII]6716,6731/H\(\alpha\) can be used (when available) instead of [NII]/H\(\alpha\), in which case it is possible to further separate AGN into Seyfert and LINER classifications. Whilst these emission lines can also be produced by O-type stars, the ratios are different due to the hard ionization spectra of the AGN. However, there remains a debate as to whether the weakest LINERs are in fact merely old, retired galaxies and not true AGN at all (e.g. Heckman & Best, 2014; Herpich et al., 2016).

Whilst dust absorption does affect the size of the emission lines, the lines used within the BPT diagram are considered to be sufficiently close that it effects the line ratios in roughly the same proportions (Buttiglione et al., 2010). As a result, provided the emission lines remain visible, the BPT method is still considered reliable and generally agrees with other identification methods.

Real galaxies may contain both AGN and star-forming regions so that the host’s position on the BPT diagram is determined by the relative contribution of these regions. This is a particular problem for the weakest AGN, generating the weakest emission lines, as it remains difficult to separate them from star-forming galaxies. Different authors have therefore defined different criteria to separate AGN from star-forming galaxies using the BPT diagram. For example, Kewley et al. (2001) used stellar population models to define an upper limit for star-forming galaxies while Kauffmann et al. (2003b) used empirical methods to define a more complete selection of AGN. Sometimes galaxies that fall between these two criteria are referred to as Composite galaxies (Heckman & Best, 2014). Further theoretical work by Stasinska et al. (2006) showed that even the more inclusive Kauffmann
et al. line may misclassify sources with very low level AGN activity as star-forming causing them to define their own demarcation criteria. Overall, the further a galaxy is to the right of the classification line, the more likely it is to be a genuine active galaxy.

Unfortunately, the BPT diagram requires a measurement of at least four emission lines meaning that there is a substantial population of galaxies with weak emission lines that cannot be classified using this method (Cid Fernandes et al., 2010). Cid Fernandes et al. attempted to address this by comparing the ratio of two lines ([NII]/Hα) with the equivalent width of the Hα line, $W_{H\alpha}$. The resulting WHAN diagram is capable of classifying more galaxies than the BPT diagram but inevitably even this method cannot classify those AGN generating the weakest emission lines.

### 2.2.2 Radio Loudness Methods

The easiest, most reliable, way to identify radio-loud galaxies is via their radio emission. For any given galaxy if we know the details of the stellar population it is possible, in theory, to calculate the amount of radio emission caused by star formation processes. Any observed excess in radio emission would then indicate the presence of an AGN. The major problem with these methods is that because the radio jets produced by AGN can extend up to several Mpc in size, identifying the correct host can be difficult. Visual identification can be done for small numbers of sources though for larger samples automated methods need to be used such as the maximum likelihood method (e.g. Williams et al., 2019).

Ordinary star-forming galaxies have a very tight correlation between radio and far-infrared luminosities (Condon, 1992; Molnar et al., 2021). The radio-far infrared relation can therefore be used to identify radio galaxies since the presence of radio jets cause a radio excess in the correlation (e.g. Ibar et al., 2008; Mingo et al., 2016). Unfortunately, the lack of sufficiently deep data from wide area infrared surveys limits the usefulness of this technique to low redshifts.

Using low-frequency 150 MHz images taken by LOFAR of the H-ATLAS field, Gurkan et al. (2018) identified a relation between the star formation rate and the radio luminosity
2.2. Identifying AGN

typical of star-forming galaxies. Gurkan et al. also found that at these frequencies, low-luminosity star-forming galaxies produce more radio emission than would be expected by simply extrapolating from more luminous galaxies with the break occurring around 1.02 $M_\odot$ yr$^{-1}$. This may be because at very low star formation rates alternative methods for producing radio emission become more significant such as pulsars or type Ia supernova.

Alternatively, Kauffmann et al. (2008) used $H_\alpha$ as a proxy for the star formation rate and compared it to the 1.4 GHz radio luminosity identifying a criteria that could be used to separate star-forming and radio loud galaxies. However, Sabater et al. (2019) showed that there is a region on this plot where both radio-loud AGN and star-forming galaxies can be found and so they proposed two separate lines that can be used to identify star-forming galaxies, radio-loud galaxies and indeterminate galaxies.

Best et al. (2005b) used the theoretical galaxy evolution models of Bruzual & Charlot (2003) to calculate the evolution of the radio emission at 1.4 GHz with the predicted strength of the 4000 Å break lines, $D_{4000}$, for a star-forming galaxy as the host ages. By comparing the $D_{4000}$ line strength with $L_{1.4GHz}/M_*$ they identified a line that could be used to separate star-forming and radio-loud galaxies. Using a larger sample, Kauffmann et al. (2008) identified that the original separation was misclassifying sources with low values of $L_{1.4GHz}/M_*$ and went on to propose a modified separation which was subsequently adopted by Best & Heckman (2012). Recent work by Sabater et al. (2019) has shown that the region between the original and modified separation criteria is populated by a mix of radio-loud and star-forming galaxies. Therefore, as discussed in Section 4.2, the AGN classifications used in this thesis are based on a mixture of classification techniques.

2.2.3 Infrared Methods

Within this thesis I use infrared data from NASA’s Wide-field Infrared Survey Explorer (WISE, see Section 3.1.3), therefore throughout this section I refer to the WISE frequency bands W1-W4 (3.4, 4.6, 12 and 22 $\mu$m respectively).

In addition to the radio-far infrared correlation discussed in Section 2.2.2, the infrared colour of the host galaxy can also be used to identify AGN activity. W3 correlates to star formation rate and W2 with stellar mass, the $W2 - W3$ colour can be used to identify regions of warm dust powered by star formation (Cluver et al., 2014; Herpich et al., 2016). The higher $W2 - W3$ values typically exhibited by star-forming galaxies allow WISE colours to be used to define a locus occupied by AGN. In the example shown in Figure 2.4 the locus occupied by AGN in the $W2 - W3$ v Concentration Index (CI) plane is shown.

Using data from the WISE survey, Herpich et al. (2016) identified sources with a $W2 - W3$ colour of less than 2.5 (0.7 in Vega magnitudes) as being radio-loud galaxies. Unfortunately this does not give a clean separation so that its results are best treated as being suggestive of a radio-loud AGN rather than conclusive (e.g. Sabater et al., 2019).

An alternative way of identifying AGN is to use the WISE $W2 - W3$ v $W1 - W2$ colour-colour plot. However, this is not very good at cleanly selecting AGN (Assef et al., 2013; Hardcastle et al., 2019), something that is especially true at low luminosities. For
Chapter 2. AGN and their Hosts

Figure 2.4: The distribution of galaxy classes in the $W_2 - W_3$ vs Concentration Index (CI) plane. CI is defined as the ratio between the 90 and 50 per cent Petrosian radii. SF are star-forming galaxies, sAGN are AGN with strong emission lines (i.e. Seyferts), wAGN are AGN with weak emission lines (e.g. LINERs), ELR and LLR (emission-line retired and line-less retired respectively) are galaxies where star formation has ceased and any ionization is due to hot low-mass evolved stars. Contours are the 95th percentile of each class with the shaded regions containing 90, 75, 50 and 25 per cent (from outside to inside) of all galaxies. Figure reproduced from Herpich et al. (2016).

example, Mateos et al. (2012), who define a wedge typically occupied by AGN, found that less luminous AGN migrate towards the region typically thought of as being dominated by star-forming galaxies (see also Assef et al., 2013). Mateos et al argue this is especially true of type 2 AGN. This result was confirmed more recently by Herpich et al. (2016) who found that many LINERs appear in the star-forming region of the WISE colour-colour plot, a trend that becomes more significant as AGN activity decreases with the fainter LINERS, where emission is dominated by stellar emission, appearing in the same part of the plot as star-forming galaxies.

The WISE colour-colour plot was recently revisited by Hardcastle et al. (2019) who, did the inverse of Mateos et al., defining a region typically avoided by radio-loud AGN. Hardcastle et al. acknowledge that this does not provide a clean separation, plus this technique cannot identify star-forming galaxies that also host AGN. The use of observed rather than rest-frame colours mean this technique is best suited to low redshift sources.

2.2.4 X-ray Methods

Whilst radiative-mode AGN produce both hard and soft X-rays, it is the hard X-rays that are generally used to identify AGN as they are less easily obscured (e.g. Marchesi et al., 2016; Murray et al., 2005a). As a result, when using hard X-rays only Compton thick AGN cannot be identified. Unfortunately, jet-mode AGN produce far fewer X-rays, so that X-ray methods are generally not used to identify radio-loud AGN. As a result, X-ray methods to identify AGN have not been used within this work and so I do not consider them any further.
2.3 AGN Host Properties

2.3.1 Jet Mode Hosts

Using a combination of the BPT plot and both the $D_{4000}$ vs $L_{1.4GHz}/M_*$ and $L_{Hα}$ vs $L_{1.4GHz}$ radio-loudness plots, Best & Heckman (2012) identified a sample of 18,286 radio-loud AGN. Using optical data for these sources taken from the SDSS catalogue, Heckman & Best (2014) compared the radiative and mechanical (i.e. jet) luminosities as a function of several host galaxy properties. Some of the key relations are shown in Figure 2.5. The [OIII] luminosity is used for the radiative luminosity, $L_{\text{rad}}$ whilst the mechanical luminosity of the jets is derived from the 1.4 GHz radio luminosity using the relation of Heckman & Best (2014) (Equation 2 in their paper), which assumes a single relation between jet power and radio luminosity:

$$L_{\text{mech}} = 28 \times 10^{36} (L_{1.4GHz}/10^{25} \text{ W Hz}^{-1})^{0.68} \text{ W}$$

(2.1)

The radio galaxies that this thesis is primarily concerned with are dominated by their mechanical luminosity. From the leftmost plot in Figure 2.5 it can be seen that radio galaxies are hosted by the most massive galaxies with the point above which radio galaxies start to appear being slightly below $10^{11}M_\odot$. For low-luminosity radio galaxies the relation is even more stark with Sabater et al. (2019) finding that all galaxies with a stellar mass above $10^{11.5}M_\odot$ have a radio-loud AGN with $L_{150 MHz} > 10^{21}$ W Hz$^{-1}$. For galaxies with masses above about $10^{11.5}M_\odot$, the jets from radio galaxies become the dominant means by which energy is output. The middle plot shows that radio galaxies also have very high stellar surface mass densities (typically above $\mu_* \sim 10^{8.5} M_\odot \text{kpc}^{-2}$) indicating the need for a high central density of stars in order to produce jets. Finally, the rightmost plot shows that the hosts of radio galaxies tend to have high values for the 4000 Å break (typically above 1.7) indicating that they tend to be hosted by older galaxies.
Using the SDSS filters, the colour of a galaxy is most commonly determined as u-r with a value greater than 2.2 typically being classified as red (e.g. Kaviraj et al., 2015b; Strateva et al., 2001), though some authors have relied on the relationship between age and colour to use the 4000 Å break as a proxy for host galaxy colours (e.g. Janssen et al., 2012). Studies at low redshift have consistently shown that radio galaxies are more likely to be hosted by red galaxies than by blue (Heckman & Best, 2014). These results have led to the overall characterisation of radio galaxies as being hosted by massive, red, dead elliptical galaxies. Though the situation may be different at high redshift, radio galaxies within the local universe therefore fall mostly on the red sequence of galaxies which strongly suggests a key role for radio jets in providing the feedback necessary to regulate the star formation rates of their hosts.

The likelihood of a galaxy hosting a radio-loud AGN is proportional to the stellar mass (Heckman & Best, 2014) suggesting that the same gas that is fuelling AGN activity is also forming stars. This link was initially confirmed for all radio galaxies by Best et al. (2005b) where it was found that the fraction of galaxies classed as radio-loud is proportional to $M_{\star}^{2.5}$. This trend was recently confirmed by Sabater et al. (2019) who found that the most massive galaxies ($>10^{11}$ M$_{\odot}$) all display at least some AGN activity when viewed at 150 MHz. This relation, combined with the lack of cold gas in most elliptical galaxies (the hosts of most radio-mode AGN) suggests that both the AGN and star formation is being fuelled by accretion from the surrounding hot environment, strengthening the case for the importance of feedback in radio-loud galaxies.

The masses of the central SMBH can be derived by modelling the movements of stars and gas around the galaxy centre (Kormendy & Ho, 2013). However, there are very few systems where this has been done and so it is more common to estimate the SMBH mass using the observed relation between either SMBH and bulge mass (e.g. Magorrian et al., 1998; Merritt & Ferrarese, 2001) or the relation between SMBH and velocity dispersion, the well-established $M-\sigma$ relationship (e.g. Tremaine et al., 2002; McConnell & Ma, 2013; Woo et al., 2013; Graham & Scott, 2013). The $M-\sigma$ is a particularly tight relation with very little scatter (Ferrarese, 2002) and is frequently cited as strong evidence of feedback from the SMBH affecting the host’s evolution (e.g. King, 2003; Fabian, 2012; Silk & Mamon, 2012; Heckman & Best, 2014). Fortunately, studies have shown that the $M-\sigma$ relationship does not depend upon whether a galaxy is active (Woo et al., 2013). Using the $M-\sigma$ relation, it has been found that the SMBHs at the centre of radio galaxies are particularly large with masses typically in the range $10^8$ - $10^{9.5}$ M$_{\odot}$ (Heckman & Best, 2014).

Since the mass of the SMBH is observed to be related to the stellar mass of the host’s bulge (e.g. Haering & Rix, 2004) and since the likelihood of a galaxy hosting a radio-loud AGN is proportional to stellar mass, it is not surprising that the chances of a galaxy hosting a radio-loud AGN is also proportional to the SMBH mass (Best et al., 2005b), though it should be noted that Sabater et al. (2019) found the chances of a galaxy hosting a radio-loud AGN is more closely related to stellar mass than with SMBH mass. However, even though the chances of a galaxy hosting a radio-loud AGN depends on SMBH mass,
the luminosity of the radio jets is independent of SMBH mass. For the most powerful sources emission line strength and radio luminosity are correlated, though this is not true for less luminous sources and there is no correlation at all below $L_{1.4\text{GHz}} \sim 10^{25} \text{ W Hz}^{-1}$, though there are suggestions that this may be due to large-scale surveys lacking the angular resolution to observe small-scale jets (Jarvis et al., 2019). It is also noteworthy that this is similar to the characteristic luminosity at which FRIIs replace FRIs as the dominant radio AGN population.

Having derived the SMBH masses it is possible to calculate the Eddington ratio, which is defined as the observed bolometric luminosity divided by the Eddington luminosity ($L_{\text{bol}} / L_{\text{Edd}}$). Applying these techniques, it has been found that jet-mode radio galaxies have very low Eddington ratios typically below 0.01 (Mingo et al., 2014; Heckman & Best, 2014).

### 2.3.2 Radiative Mode Hosts

The leftmost plot of Figure 2.5 shows that, at least within the local Universe, the least massive hosts produce radiative-mode AGN with a luminosity that is proportional to mass up to a break point of about $10^{10.5} \text{ M}_\odot$. This break point can also be used as the characteristic break between the two AGN populations. Since radiative-mode hosts tend to be smaller in mass than jet-mode hosts, it is to be expected that the SMBH masses are smaller too, with masses between $\sim 10^{6.5}$ to $10^8 \text{ M}_\odot$ (Heckman & Best, 2014). The middle plot shows the luminosity of both AGN populations falling below $10^{8.5} \text{ M}_\odot$ indicating a common requirement for AGN to be hosted by galaxies with a high central mass density. The rightmost plot shows a clear preference for radiative-mode AGN to be hosted by younger galaxies.

The high mass density and young ages of radiative-mode AGN shows they are most active where there is a large supply of cold gas which in turn implies high star formation rates. Secular processes are believed to drive the cold gas towards the galactic centre, fuelling the AGN. Several groups have researched this, finding a sub-linear relation between AGN luminosity and star formation rates (e.g. LaMassa et al., 2013; Diamond-Stanic & Rieke, 2012). This relation does not appear to hold for sources with radio luminosities below $\sim 10^{44} \text{ erg s}^{-1}$ at low redshifts (Rosario et al., 2012). Caution should however be exercised when applying the above correlations to ensure only the star formation rate of the central regions are considered.

Due to the young ages of radiative-mode hosts, they also tend to appear to be blue in colour (Heckman & Best, 2014; Kaviraj et al., 2015a). However, since dust is also often used as a proxy for cold gas, it has been found that reddening is stronger in these galaxies (Kauffmann et al., 2008) strengthening the idea that radiative-mode AGN are fuelled by a plentiful supply of cold gas.

This association with young, star-forming galaxies means that radiative-mode AGN are generally found in more disc-like galaxies (Miraghaei & Best, 2017). Due to their young hosts it is not surprising that there is also a relation with pseudo-bulges (Kormendy & Ho,
Chapter 2. AGN and their Hosts

2013). Pseudo-bulges (or discy-bulges) form before the classical (de Vaucouleur profile) bulge. Consequently, pseudo-bulges have higher velocity dispersions, contain more cold gas and are populated by younger stars than classical bulges. Pseudo-bulges also often show additional structures such as spiral arms and bars. It can also be shown that the torque exerted on the cold gas by the non-axisymmetric distribution of stars within pseudo-bulges can efficiently drive gas inwards towards the SMBH.

If non-axisymmetric distributions are responsible for fuelling AGN then barred galaxies would be more likely to host radiative-mode AGN, however no direct link has been found (Cisternas et al., 2013). Further doubt on the necessity of bulges as a mechanism for driving gas inwards towards the central regions of radiative-mode AGN comes from the fact that some (rare) AGN appear to have no bulge at all (Simmons et al., 2013). However, if bulges are not responsible for the secular evolution of radiative-mode AGN then it is a mystery what is.

However, as noted in Section 1.1, only a small fraction of radiative-mode AGN produce jets. Comparing this subset with jet-mode AGN, Hardcastle & Croston (2020) emphasise that the general trends seen above remain true with radiative-mode radio loud AGN typically being found in bluer hosts with higher star formation rates and lower stellar masses. Whilst these properties do suggest a more disc-like host, and whilst there are examples of spiral-hosted radio loud AGN (e.g. Kaviraj et al., 2015b; Mulcahy et al., 2016), the overwhelming majority of radio galaxies are found in ellipticals. However, amongst the subset of powerful FRIIs (of which the majority are radiative-mode) about 50 per cent show some morphological disturbance compared to pure elliptical galaxies (Smith & Heckman, 1989; Tadhunter, 2016a). As noted by many authors, this may suggest a link between mergers and AGN activity (e.g. Di Matteo et al., 2008; Li et al., 2008; Tadhunter, 2016a).

Overall, it appears that the existence of radio jets is strongly linked with stellar mass (Sabater et al., 2019), irrespective of whether an AGN is radiative or jet-mode. Hardcastle & Croston (2020) argue that this is because the host’s mass is linked to accretion rate with only the most massive galaxies being able to achieve a sufficient accretion rate to generate radio jets.

2.3.3 Environments

Observationally, AGN are found in a wide range of environments. However, radiative-mode AGN preferentially avoid dense environments with the frequency of radiative-mode AGN at a fixed stellar mass decreasing by a factor of two from the field towards the centre of group/cluster environments (Heckman & Best, 2014). This trend is particularly pronounced for late-type radiative-mode galaxies where their frequency has already decreased at the cluster virial radius whereas for early-type radiative-mode hosts the frequency starts decreasing closer to the cluster centre (Hwang et al., 2012).

In contrast, jet-mode AGN are preferentially found in group/cluster environments, though it should be noted that they occupy a wider range of environmental densities than radiative-mode AGN (Gendre et al., 2013). In particular the majority of the brightest
cluster galaxies (BCGs) tend to host jet-mode AGN (Best et al., 2007). This may be because BCG’s tend to be more massive and are therefore more likely to generate radio jets (Sabater et al., 2019), though it is also possible that the denser environment surrounding the BCG confines the lobes more, reducing adiabatic losses and causing more radio emission at lower power, making them easier to observe (Barthel & Arnaud, 1996).

This has led to the suggestion that it is the environment that is the primary driver of whether an AGN is jet-mode or radiative-mode (e.g. Ineson et al., 2015; Hardcastle & Croston, 2020). According to this picture the large reservoirs of cold gas available in young, star-forming galaxies (which are mostly found in sparse environments) lead to high accretion rates and radiative-mode AGN. In contrast the large galaxies, that are more likely to be found in dense environments, accrete material from the hot environment leading to lower accretion rates and jet-mode AGN (Gaspari et al., 2015). As a result, jet-mode AGN take part in a feedback loop where the energy from the jets is heating the surrounding environment, restricting the cooling rates of the gas that is fuelling the AGN.

However, as Hardcastle & Croston (2020) note, whilst the environment favours a particular type of AGN, it is not necessarily determinative as there is no reason why accretion from a hot gas environment cannot generate the accretion rates necessary to fuel radiative-mode AGN. Therefore, whilst most sources will follow the pattern described here, exceptions are to be expected. For example, NGC 1275 is a radiative-mode AGN despite being seemingly fuelled by the hot environment.

Hardcastle (2018) has suggested that the accretion mode is determined by the ratio between the accretion rate and black hole mass, $\dot{M}/M_{BH}$ with smaller ratios resulting in jet-mode AGN. According to this view the reason for the large number of jet-mode AGN observed in dense environments is due to these host galaxies typically having large SMBH masses and low accretion rates caused by the accreting material cooling relatively slowly from the surrounding environment. Equally, the large gas reservoirs found in field galaxies, coupled with their smaller SMBH masses favours radiative-mode AGN.

This link between environment and accretion is supported by the findings of Ineson et al. (2015) that for jet-mode AGN, whilst radio luminosity and environmental richness are related, there is no relation with SMBH mass. This has recently been confirmed by Croston et al. (2019) who found that, at redshifts up to at least 0.35, the luminosity of jet-mode AGN tends to increase proportionally with the richness of the environment. Croston et al. did not find any relation between host mass and cluster richness strengthening the case for environmental as opposed to secular fuelling as it shows the luminosity-richness relation is not driven by the host’s mass.

Irrespective of the fuelling source, radio galaxies drive lobes of plasma into their environments. Whilst it is widely believed that most if not all, sources go through a period where these lobes are overpressured with respect to the surrounding environment allowing them to expand supersonically driving shocks (e.g. Heinz et al., 1998), the minimum requirement for the lobes to survive and remain visible is that they must be in pressure balance.
Chapter 2. AGN and their Hosts

For powerful FRII galaxies, Ineson et al. (2017) used inverse Compton measurements, combined with radio observations to calculate the internal lobe pressures and compare them with the external environmental pressure. Acknowledging a spread in values, Ineson et al. (2017) find that overall the lobes are in pressure balance with the surrounding environment. This suggests that the radio-emitting electrons are sufficient to account for the internal lobe pressure without having to consider a proton content.

Unfortunately, as described in Section 1.3.2, it is not normally possible to perform the same calculations for FRI galaxies with equipartition pressure estimates showing that the electron population alone cannot provide sufficient pressure to balance the external medium (Morganti et al., 1988; Dunn et al., 2005; Croston et al., 2018). As mentioned in Section 1.3.2, non-radiating particles entrained from the environment are believed to supply the additional pressure.

This in turn suggests a link between the FR class of a source and the environment, though several studies have found that accretion mode is more strongly linked to environment than the radio morphology (Gendre et al., 2013; Ineson et al., 2015). This suggests that the relation between environment and morphology is a secondary relation driven by the fact that most jet-mode AGN produce FRI-type galaxies with the morphology depending upon the interplay between jet power and the surrounding environment (Mingo et al., 2019; Hardcastle & Croston, 2020).

2.4 Feedback

In order to obtain a realistic looking universe with the range of observed properties, cosmological simulations require some form of AGN feedback (e.g. Somerville & Davé, 2015; Naab & Ostriker, 2017). Feedback can be either positive (i.e. leading to enhanced star formation) or negative (i.e. quenching star formation and black hole growth). AGN feedback can also be (a) ejective, removing material from the host galaxy or (b) preventative whereby material is prevented from being accreted by the host galaxy. In general, disc winds are believed to be ejective, terminating star formation and causing a galaxy to move from the blue cloud to the red sequence whilst radio jets are believed to be preventative, transporting energy into the hot intragroup/intracluster medium, restricting cooling rates and, as a result, limiting the rate at which host galaxies can accrete from their environments (Fabian, 2012; McNamara & Nulsen, 2007). It should however be noted that a single process can be simultaneously preventative and ejective. For example, there may be local pockets where disc winds act in a positive manner to enhance star formation. Noting that the situation may be different at high redshifts, AGN feedback in the local Universe is discussed below in relation to the two AGN modes.

2.4.1 Radiative-Mode AGN

Since radiative-mode AGN are generally hosted by young star-forming galaxies feedback from both the stellar population and the SMBH must be considered.
2.4. Feedback

Stellar Feedback

Stellar feedback in the form of galactic winds comes from supernovae ejecta, radiation from stars and solar winds. There is little doubt that these winds carry sufficient energy to dramatically affect the cold gas within a galaxy. Chen et al. (2010) used sodium (Na) absorption lines to trace galactic winds and showed that they form wide angle bipolar outflows along the host’s minor axis. These bipolar outflows are caused by a pressure gradient within the ISM, can be seen at low radio frequencies (Kharb et al., 2016) and can affect the surrounding gas out to the galaxy’s virial radius (Heckman et al., 2017).

It is generally believed that stellar feedback is more important in providing feedback in smaller host galaxies whereas in larger galaxies the large energy output of a central AGN dominates. There is evidence for this in the observed galaxy luminosity function (see Figure 2.6). Silk & Mamon (2012) argued that the energy supplied by supernova was sufficient to reduce the star formation efficiency in smaller galaxies causing the observed differences from theory at lower luminosities. In larger galaxies the outflow from supernovae is insufficient to counteract the large inflows of gas with the result that AGN feedback is invoked to explain the shape of the observed luminosity function. Theoretical models incorporating stellar and AGN feedback have had significant success in matching the observed luminosity function (Naab & Ostriker, 2017).

Figure 2.6: The number density of galaxies as a function of their magnitude. The blue line shows the observed galaxy luminosity function and the red line shows a theoretical prediction with no feedback. Figure reproduced from Silk & Mamon (2012).


Black Hole Feedback

Based on observations of blue-shifted absorption lines in mm/sub-mm, optical, UV and soft X-ray of type 1 radiative-mode AGN, it is well-established that these sources can drive outflowing winds (Fabian, 2012). These winds are estimated to contain between 200 and 500 times the mass that is accreted by the SMBH (Qiu et al., 2021). The speeds of these winds are believed to range from several hundred km s\(^{-1}\) in low luminosity AGN to tens of thousands of km s\(^{-1}\) in the most luminous quasars (Heckman & Best, 2014).

Unfortunately, the amount of mass being carried by these winds (and hence their effect on galaxy evolution) has proved difficult to constrain due to the absorption lines used to detect them being saturated (Heckman & Best, 2014). Further, direct observations of such outflows still only extend to the kpc regime potentially limiting the effects of such feedback. However, studies of [OIII] and H\(\beta\) emission lines in luminous quasars have shown spherical regions of ionised gas spreading out across throughout the entire host galaxy (Liu et al., 2013). Liu attributes these observations to AGN feedback that is extending across the entire galaxy potentially having a significant effect on the evolution of the host.

Jets

As already noted, there is also subset of radiative-mode AGN that produce jets. Whilst there are exceptions to this general paradigm (Hardcastle & Croston, 2020), radiative-mode objects are typically fuelled by cold gas from within the host whereas jet-mode objects are fuelled by material from the same environment into which they deposit their energy. As a result, the majority of radiative-mode jets do not participate in the feedback maintenance cycle described in Section 2.4.2. Like the jet-mode AGN described below, the energy being transported by these jets is expected to be transferred to the local environment, with the result that any cooling flows are restricted. However, the absence of any feedback cycle means there is likely to be significant differences between heating and cooling for most radiative-mode jets.

2.4.2 Jet Mode AGN

As mentioned in Section 2.3.3, whilst exceptions are expected, the majority of jet-mode AGN are ultimately fuelled by the hot gas surrounding the host (Hardcastle & Croston, 2020). This is the same hot gas that confines the radio jets and into which the lobes expand. The lobes inflate cavities or create bubbles which over time transfer their energy back into the surrounding hot gas restricting the rate at which it cools and can be accreted by the host thereby creating a feedback loop. This link with the supply of cold gas to the host is the reason why it is believed jet-mode AGN are responsible for suppressing the star formation rate at the high end of the galaxy luminosity function seen in Figure 2.6.

It was shown in Equation 1.26 that the energy loss rate for an optically thin plasma is proportional to density squared. Therefore, at the centre of clusters where the gas density is highest, the cooling time is relatively short. Without some sort of mechanism to inject
energy, cooling flows would rapidly develop bringing large amounts of material into the host and causing the central regions to cool dramatically (Fabian, 2012). This is known as the cooling catastrophe. However, observations show that the temperature of the gas in the cores of clusters is higher than predicted by theoretical models. Since radio galaxies are commonly observed in BCG’s, AGN feedback is typically invoked as the heating mechanism to prevent the cooling catastrophe.

The energy supplied by the radio jets can be calculated from either their radio or X-ray emission (Sections 1.3.2 and 1.5). Over long periods of time, the energy transported by the jets is roughly in balance with the cooling losses (Best et al., 2006; McNamara & Nulsen, 2007; Hardcastle et al., 2019). However, the jets and lobes are anisotropic structures whilst the hot gas is a far more isotropic structure. In order for feedback to be efficient the energy deposited by the lobes must be distributed evenly throughout the gas. A number of mechanisms have been suggested (Bourne & Sijacki, 2017) including:

- shocks
- sound waves
- mixing
- turbulence
- cavity heating
- cosmic rays

Of particular relevance to this research are shocks, which have been observed to occur in relatively isolated galaxies (Kraft et al., 2003; Croston et al., 2007, 2009), to groups (Randall et al., 2015) and clusters (Forman et al., 2007; Croston et al., 2011). These shocks cover a range of scales from a few tens of kpc to hundreds of kpc in size. The Perseus cluster seems to offer support for weak shocks or sound waves as concentric rings can be seen in X-ray images that are associated with intermittent AGN activity inflating bubbles within the ICM (Fabian et al., 2003, 2006; Sanders et al., 2016). According to this theory the weak shocks slowly transfer energy back to the ICM as the bubbles gradually expand thereby ensuring an isotropic release of energy (Fabian, 2012).

However weak shocks are very poor at transferring energy and so Bourne & Sijacki (2017) argue that substructures within clusters continually stir the ICM introducing local pockets of turbulence throughout that can then efficiently transfer heat. By including such substructures within their model, they are able to reproduce the velocity dispersion maps and contours observed in the Perseus cluster by the Hitomi satellite (Hitomi Collaboration et al., 2016).

Whilst BCG galaxies offer very dramatic examples of jet-mode feedback, Best et al. (2007) have extended this work to include a wider selection of ellipticals drawn from the SDSS survey. They found that when moving from the largest clusters towards groups the
rate of heating decreased slower than the rate of cooling so that in the smaller clusters it appears the jets produce more energy than is needed to offset cooling.

This difference is believed to be because in smaller systems much of the energy carried out by the jets is ultimately deposited outside of the feedback system so that only a fraction of the energy transported is actually used to offset cooling. Further, the duty-cycle is believed to be different in smaller galaxies with the jet being ‘off’ for a larger percentage of the time so that in order to maintain a long-term balance the jets have to dramatically over-heat the gas during those times when the jet is turned on.

### 2.5 Small Radio Galaxies

The size and luminosity of larger radio galaxies means they are far easier to identify and study, consequently very little is known about either the number density or the effects that smaller radio galaxies can have upon the evolution of their host galaxies. Following on from previous work that shows these physically small jets are capable of producing detectable shock structures (Croston et al., 2007; Mingo et al., 2012; Hota et al., 2012), the GSJ studied in this thesis (see Chapter 4 for a full definition) are resolved sources, making them distinct from the FR0 class of objects (Baldi et al., 2015, 2018b). GSJ exist at a stage of evolution when they are large enough to have escaped the dense environment at the core of the host whilst remaining small enough to have a direct effect upon the host’s evolution.

Though not part of the definition, GSJ are typically low luminosity sources (see Section 4.4.1). Luminosity functions show that there are far more low luminosity AGN than higher luminosity, increasing with a power law down to the lowest observed flux densities (e.g. Best et al., 2005a; Sabater et al., 2019). However, this cannot continue indefinitely as otherwise there would be more low-luminosity radio-loud AGN than there are galaxies. Cattaneo & Best (2009) calculated that the turn over must be at about $10^{20.2}$ W Hz$^{-1}$ at 150 MHz, about an order of magnitude below LOFAR’s limit. In an analogy with the optical spectrum of galaxies, whilst the most massive stars are individually the most luminous, the overall spectrum is dominated by the more numerous less massive stars (e.g. Spinrad & Taylor, 1971; Meidt et al., 2014). Similarly, whilst the most massive jets are the easiest to observe and study it is possible that the more numerous, lower luminosity AGN are more important in determining the overall evolution of the universe.

From the few sources studied we do know that at least some GSJ can drive shocks into the host’s ISM (Croston et al., 2007, 2009; Mingo et al., 2011, 2012; Hota et al., 2012). This is significant since galaxy evolution models have consistently included shocks from supernovae as one of the key elements needed to explain how stars form and how galaxies evolve (e.g. Hopkins et al., 2014). Like supernovae, jet-driven shocks could also affect star formation rates, taking the form of either positive feedback, in which gas within the host is compressed leading to an increase in star formation (Markakis et al., 2018; Salomé et al., 2017; Kalfountzou et al., 2014) or negative feedback, in which gas within the host is heated
leading to a reduced SFR (Gürkan et al., 2015; Guillard et al., 2015). Therefore, whilst (like all jets) GSJ are depositing energy into their surrounding environments, it is likely many are also driving shocks into their host environment potentially having a direct effect on the host’s evolution.

In the case of Markarian 6, Mingo et al. (2011) found a GSJ where the lobes were expanding at a speed of ~Mach 3.9 driving shocks into the host galaxy ISM. Similar results were found for the Circinus galaxy (Mingo et al., 2012). The lower power of Markarian 6, $\sim 7 \times 10^{42}$ erg s$^{-1}$, is also suggestive of the possibility that many low-power jets may be capable of creating shocks that drive into the host galaxy. In the case of Centaurus A, Croston et al. (2009) also demonstrated that small, galaxy-scale jets can be powerful ($\sim 10^{43}$ erg s$^{-1}$) sources of feedback, depositing significant amounts of energy into the host ISM.

For these small sources, the radio lobes have not yet fully extended beyond the host galaxy so that regardless of any shocks present, at least some of the energy being transferred from the radio lobes is directly influencing the host. For example, NGC 3801 has radio lobes that are approximately 10 kpc across containing an energy roughly equivalent to that of the host ISM (Heesen et al., 2014). Using far-UV data to trace star formation rates, Heesen et al. (2014) note that the location of the lobes coincide with locations of reduced star formation. This does suggest that as the lobes expand they are quenching star formation though it is also possible that they are simply expanding into regions of low star formation.

Following a merger about a billion years ago, Heesen et al. (2014) find that NGC 3801 has only (relatively) recently started producing jets. Whilst NGC 3801 may be a young jet, overall it is unlikely that the population of small sources consist primarily of young/switched-off powerful radio AGN as if they were there should be no significant difference in the numbers of small and large sources found in rich environments. In fact, Croston et al. (2019) showed that there are far fewer low-luminosity sources in rich environments when compared to larger sources. Croston et al. showed that as the radio luminosity decreases, far fewer radio AGN are associated with groups/clusters with only 10 per cent of sources at $L_{150} \sim 10^{22.5}$ W Hz$^{-1}$ having an association compared to about 30 per cent at $L_{150} \sim 10^{26}$ W Hz$^{-1}$. This clearly indicates a preference for low-luminosity sources to be found in the field, reinforcing the idea that they are not simply switched-off powerful AGN.

Not only can the shocks from GSJ affect the hosts evolution, mm-studies of low-level AGN activity in intermediate mass ($M_\star = 10^{10} - 10^{11}$ M$_{\odot}$), low redshift galaxies where neither radio-jets nor powerful quasars are observed, have shown that low-level AGN activity may be responsible for destroying any molecular material accreted by the host and suppressing star formation (Schawinski et al., 2009). Schawinski et al. used molecular CO emission lines to determine the molecular content finding that about 200 Myr after the onset of star formation, AGN activity dramatically reduces the amount of molecular material within a galaxy that is available for star formation with the host’s gas reservoirs being
destroyed prior to the AGN reaching peak luminosity. It is possible that many objects traditionally classified as radio-quiet do in fact contain low-luminosity radio jets (Jarvis et al., 2019). Given that they were observing at mm-wavelengths it is therefore possible that the sample of Schawinski et al. (2009) also contain small, low-luminosity jets which may be affecting the host’s evolution.

The relation between small, compact CSS/GPS sources (Section 1.2.1) and larger radio galaxies is also uncertain. If, as is frequently assumed, CSS sources evolve into GPS sources which then evolve into the larger FRI/FRII sources (O’Dea & Saikia, 2021; Jimenez-Gallardo et al., 2019; O’Dea, 1998) then the size of GSJ mean they exist at a crucial time between these populations when the radio jets are emerging/have recently emerged from the host whilst simultaneously being small enough to be interacting/recently interacted with a substantial portion of the host’s interstellar medium. The size of GSJ also means they are potentially capable of directly affecting the evolution of their hosts, making them the ideal size for studying the importance of feedback from radio jets.

Although the samples of low-luminosity radio-loud AGN studied to date have been small and have sometime shown a wide range of results, there is some evidence that less luminous sources have flatter spectral indices (e.g. de Gasperin et al., 2018; Prandoni et al., 2006) which is in line with the idea of the radio emission being increasingly dominated by a small synchrotron self-absorbing region near the core, as is seen in CSS/GPS sources. However, whilst a recent study of over 2,000 objects by Sabater et al. (2019) found that below flux densities of $S_{1.4\text{GHz}} \sim 20\text{ mJy}$ the observed spectral index started to fall towards 0.4, this was driven entirely by selection effects and that the spectral index of smaller sources was consistent with the value of 0.63 found for the more extended, luminous sources. As a result, Sabater et al. find that rather than being core dominated, smaller sources are more similar to scaled down versions of the more extended sources. The lack of core domination also makes these sources distinct from the compact CSS/GPS sources.

### 2.6 Science Questions

In this thesis I aim to improve our understanding of the role of feedback in physically small radio galaxies whose small size means they are directly interacting with, or have recently impacted a substantial portion of, the host’s interstellar medium. Due to the high sensitivity and angular resolution of LOFAR I am able to use the wide area LoTSS survey (described in Section 3.1.1) to, for the first time, identify and study the properties of a population of GSJ. Additionally, for a subset of GSJ I use both high angular resolution radio data and X-ray images to examine the potential role of feedback in these sources.

In Chapter 3 I describe the radio and X-ray data analysis methods used throughout the remainder of this thesis. In Chapter 4 I use visual identification along with a combination of the emission line, radio loudness and infrared colour-colour plots described in this chapter to identify GSJ from within the LoTSS DR1 data set. I describe the host and radio properties of those sources identified as GSJ and examine how the probability of a galaxy
hosting a GSJ varies with the host’s stellar and black hole masses. I then calculate a first-order estimate of the amount of energy contained within the radio lobes of the GSJ and discuss the potential impact this could have upon the hosts’ evolution.

In Chapter 5 I use high angular resolution radio images of a representative sub-sample of GSJ to confirm/refute the host IDs from the value-added LoTSS DR1 catalogue and to examine the radio morphology of the sources. For those sources confirmed as GSJ I perform a detailed spectral analysis, using the results to find the ages of GSJ. I then combine the age and sizes of GSJ to produce the first estimate of the expansion speeds of GSJ allowing me to look into the possibility that they are driving shocks into their environment.

In Chapter 6 I use X-ray observations of two GSJ to look at the environments in which GSJ reside and to look for any direct evidence of shocks generated by the expanding lobes. I look at the particle content of the lobes and discuss the implications for how these small sources are interacting with their environments.

Finally, in Chapter 7 I summarise my findings and discuss what future work could be undertaken to further expand our understanding of GSJ.

Throughout this thesis I assume cosmological parameters of $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. As stated in Section 1.3, I define the spectral index, $\alpha$, using the definition of radio flux density $S_\nu \propto \nu^{-\alpha}$.
Chapter 3

Surveys and Data Analysis

In this thesis I use data from large surveys as well as dedicated observations of individual objects. The surveys used are described in Section 3.1 within which there is a particular focus on the Low Frequency Array (LOFAR, formally known as the International LOFAR Telescope) and the LOFAR Two metre Sky Survey (LoTSS), which is the main instrument/survey used within this thesis to identify radio galaxies. The Karl G. Jansky Very Large Array (VLA) and XMM-Newton (XMM) telescopes used for the dedicated observations are described in Section 3.2. In Sections 3.3 and 3.4 I describe the data reduction techniques used to analyse these observations. Finally, in Section 3.5, I provide a brief summary of the main third-party tools used within my research.

3.1 Survey Datasets

3.1.1 LoTSS

The LOFAR Two-Metre Sky Survey (LoTSS, Shimwell et al., 2019; Williams et al., 2019; Duncan et al., 2019) is based on observations taken using LOFAR, a forerunner to the Square Kilometre Array\(^1\) (SKA; for a recent review of the SKA’s progress see https://www.skatelescope.org/key-documents/). LOFAR is a revolutionary new phased-array radio telescope offering unparalleled sensitivity and angular resolution making it the ideal tool to

\(^1\)https://skatelescope.org

Figure 3.1: The two LOFAR antennas. Left: The Low Band Antenna. Right: The High Band Antenna. Source: ASTRON.
locate low-luminosity radio galaxies (for a full description see van Haarlem et al. (2013)). An introduction to how interferometers, such as LOFAR, work is given in Section 3.3.1. LOFAR is built of a large number of small omni-directional dipoles (see Figure 3.1) with the beam being created and pointed electronically. LOFAR consists of two separate designs of antenna, the Low Band Antenna (LBA) operating between frequencies of 10 and 90 MHz and the High Band Antenna (HBA) operating between 110 and 250 MHz. The LoTSS survey uses the HBA and is conducted in the frequency range of 120 to 168 MHz. Weighting each of the LoTSS sub-bands according to their noise levels produces images with an average weighted frequency of 149 MHz (Shimwell et al., 2017), more commonly expressed as a representative frequency of 150 MHz.

Run by the Dutch Institute for Radio Astronomy (ASTRON), LOFAR comprises 38 stations in the Netherlands, plus a further 14 stations across nine countries within Europe\(^2\) (see Figure 3.2). Within the Netherlands each station consists of 96 low band antennas and 48 high band antennas whilst the international stations each have 96 low and high band antennas.

The international stations give LOFAR a maximum baseline (distance between antennas) of nearly 2,000 km equating to a maximum angular resolution of \(\sim 1.5\) arcsec in the low band and \(\sim 0.3\) arcsec in the high band. Twenty-two of the Dutch stations are located within an area approximately \(2 \times 3\) km in size creating what is known as the ‘core’. This combination of long baselines and a compact core mean LOFAR is simultaneously sensitive to both compact and extended emission (see Section 3.3.1). However, as the calibration and imaging using international baselines is more challenging and considerably more computationally intensive, the first release of LoTSS (DR1), the main release used within this thesis, was conducted using only the Dutch stations giving the survey an angular resolution of 6 arcsec. At the time of writing it is anticipated that the second data release of LoTSS

\(^2\)For the most up to date status of LOFAR see \url{https://www.astron.nl/telescopes/lofar}
Figure 3.3: The sensitivity of LoTSS compared to other surveys. The horizontal lines show the frequency coverage for those surveys with a large bandwidth. The circles represent the relative angular resolution and the green and blue lines represent the equivalent sensitivity that would be required to see the same objects with a spectral index of 0.7 and 1.0 respectively. Figure reproduced from Shimwell et al. (2017).

will also be at an angular resolution of 6 arcsec but, for this release, data is also being recorded using all the international baselines so that eventually it will be possible for users to make higher angular resolution images of individual fields.

The ∼6 arcsec resolution of LoTSS DR1 combined with its sensitivity of ∼70 µJy beam$^{-1}$ make it the most sensitive and highest angular resolution wide area radio-survey to date (see Figure 3.3). Whilst the LoTSS survey will eventually cover the entire northern sky, DR1 covers the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) Spring field, an area of sky 424 deg$^2$ in size (about 2 per cent of the sky area to be covered) between right ascension 161.25° - 232.5° and declination 45° - 57° which covers most of the constellation Ursa Major and extends towards Draco (Shimwell et al., 2019). The HetDex spring field contains almost 320,000 radio sources of which ∼60,000 are resolved (Williams et al., 2019). LoTSS therefore identifies ∼10 times as many sources as the earlier FIRST radio survey (Becker et al., 1995) and ∼20 times as many as the NVSS survey (Condon et al., 1998) over the same area.

231,716 of the sources identified by LoTSS (about 70 per cent) have been associated with an optical host from either PanSTARRs (Chambers et al., 2016) or WISE (Wright et al., 2010). These optical counterparts, along with some of the key data relating to the optical hosts, are listed in an additional value-added catalogue (Williams et al., 2019). The optical identifications were done by firstly using the Python Blob Detector and Source Finder (pyBDSF; Mohan & Rafferty, 2015) algorithm to create a set of ellipses where each
ellipse is associated with a separate piece of radio emission. The identification of the host
galaxy for simple sources was then done using a maximum likelihood algorithm. For more
complex sources this identification was done via a Zooniverse-based application where a
team of expert volunteers, of which I was a part, visually inspected and identified the host
galaxies. As a result, I became a co-author on the resulting paper: Williams et al. 2019.

In addition to listing the optical counterparts, the value-added catalogue also contains
photometric redshifts calculated for 53 per cent of the resolved sources using a Bayesian
machine learning algorithm (Duncan et al., 2019). Where possible spectroscopic redshifts
from the Sloan Digital Sky Survey (SDSS) have also been associated with the sources. It
should be noted that within this thesis I make use of the data catalogues and reduced
images produced by the LoTSS team rather than processing the raw LOFAR data myself.

The key scientific goals behind the LoTSS project can be broken down into several
projects, each with its own principal investigator and with the last being effectively a
catch-all grouping. These projects are:

- Highest redshift radio sources
- Clusters and cluster halo sources
- Evolution of AGN and star-forming galaxies
- Detailed studies of low-redshift AGN
- Nearby galaxies
- Gravitational lensing
- Galactic radio sources
- Cosmological studies
- Projects outside existing working group areas

This project is part of the ‘Detailed studies of low-redshift AGN group’. This group
is focused on uncovering the inter-relationships and dependencies seen at low redshifts
between the energy released by AGN feedback, the global properties of the host galaxy
and the stage in the life cycle of the host.

In the future, once the William Herschel Telescope Enhanced Area Velocity Explorer
(WEAVE) instrument is completed at the William Herschel Telescope (WHT) all LOFAR
detected sources will be followed up and where possible spectroscopic data will be obtained.
This is known as the WEAVE-LOFAR survey (Smith et al., 2016).

3.1.2 Sloan Digital Sky Survey (SDSS)

SDSS is an ongoing optical survey covering over 14,500 square degrees including the entire
northern sky, within this thesis I make use of data release 14 (DR14). SDSS has identified
over a billion separate objects including over two million separate galaxies, many of
3.1. Survey Datasets

them spectroscopically (Abolfathi et al., 2018). SDSS takes observations in five wavebands centred on 3551 Å, 4686 Å, 6165 Å, 7481 Å and 8931 Å. These are designated as bands u, g, r, i and z, and can see objects down to magnitudes 22.0, 22.2, 22.2, 21.3 and 20.5 respectively. SDSS has a maximum spatial resolution of 0.396 arcsec.

DR14 contains many of the basic parameters used to estimate galaxy properties such as their size, redshift and luminosity in each of the five bands. However, one of the problems encountered when using SDSS has been that when measuring the half-light radii of galaxies SDSS does suffer from sky subtraction problems with the result that for galaxies with radii larger than 5 arcsec the size and brightness of the galaxy is underestimated (Bernardi et al., 2010). Whilst this affects only a small percentage of SDSS objects (about 6 per cent) it is generally the lower redshift galaxies that are affected, the same population of galaxies that host the GSJ studied in this thesis.

Included with DR14 are several value-added catalogues including data derived from the MPA-JHU pipeline\(^3\) (Kauffmann et al., 2003a; Brinchmann et al., 2004; Tremonti et al., 2004). This value-added catalogue was created by the Max Planck Institute for Astrophysics (MPA) and the John Hopkins University (JHU) and provides galaxy properties derived from the spectrographic data such as stellar masses, oxygen abundances and specific star formation rates. The data in this catalogue comes from the model that best fits the spectral data. The data in these catalogues are therefore not only limited to those objects with spectroscopic data but also by the quality of the fit. Unfortunately, because many of the sources used in this project are faint, SDSS spectra are not always available and so many of my sources do not appear in the MPA-JHU catalogue.

One of the key parameters used within this thesis to estimate SMBH masses is the SDSS velocity dispersion measurement (see Section 2.3.1). For a group of gravitationally bound objects, such as stars in a galaxy, velocity dispersion measures the statistical dispersion in velocities around the group’s average velocity. The velocity dispersion in SDSS is the measure of stellar kinematics within the bulge and, according to the virial theorem, is directly related to the total gravitational potential (Zahid et al., 2016).

SDSS also define a ‘main galaxy sample’ which is a complete sample of galaxies within its magnitude limits. Used within this thesis, the main galaxy sample is defined as all those galaxies with an r-band Petrosian magnitude greater than or equal to 17.77 and a half light mean surface brightness less than or equal to 24.5 mag arcsec\(^{-2}\) (Strauss et al., 2002). The surface brightness is found according to the formula:

\[
S(\text{mag/arcsec}^{-2}) = m + 2.5 \log_{10}(A) \tag{3.1}
\]

where \(m\) is the apparent Petrosian magnitude and \(A\) is the surface area covered by the half-light Petrosian radius. Those galaxies that are within the main galaxy sample have the ‘GALAXY’ flag set in the primTarget field. The main galaxy sample is 99 per cent complete. The size of the fibres used to measure the spectroscopy of galaxies means that

\(^3\)http://www.sdss3.org/dr9/algorithms/galaxy_mpa_jhu.php
Chapter 3. Surveys and Data Analysis

galaxies need to be at least 55 arcsec apart to be measured. As a result, about 6 per cent of the galaxies in the main galaxy sample cannot have spectroscopic measurements taken.

3.1.3 WISE

The Wide-field Infrared Survey Explorer (WISE) was a satellite that was in operation between December 2009 and September 2013. It conducted an all sky survey measuring over 747 million sources at 3.4, 4.6, 12 and 22 µm, known as bands W1, W2, W3 and W4 respectively (Wright et al., 2010). WISE was a highly sensitive instrument achieving sensitivities of up to 0.08, 0.11, 1 and 6 mJy at angular resolutions of 6.1, 6.4, 6.5 and 12 arcsec respectively in its four bands. During its operational life WISE detected over 563 million objects with a minimum signal to noise ratio of 5. When observing galaxies, the W1 and W2 bands are dominated by stellar emission whilst the W3 and W4 bands are sensitive to emission from warm dust that can be due to star formation (Herpich et al., 2016) or due to AGN heating a dusty torus though it should be noted that the W4 band has a poorer signal to noise ratio than the other bands.

3.1.4 FIRST

The Faint Images of the Radio Sky at Twenty Centimeters (FIRST) is a radio survey conducted at 1.4 GHz with a limiting sensitivity of 1 mJy that covers the same sky area as SDSS. Throughout this thesis I treat FIRST as having a largest angular scale of 30 arcsec which is the angular size at which FIRST is sensitive to 77 per cent of the total flux density. FIRST images have an angular resolution of 5 arcsec and a typical rms of 0.15 mJy. Full details of the survey can be found in Becker et al. (1995).

3.1.5 NVSS

Completed in 2002, the NRAO VLA Sky Survey (NVSS) is a radio survey conducted at 1.4 GHz using the VLA’s ‘D’ configuration (see Section 3.2.1) and covers the entire northern sky above a declination of ∼ −40°. NVSS is less sensitive than FIRST having a limiting sensitivity of 2.5 mJy, however NVSS is sensitive to larger scale emission of up to about six arcminutes. NVSS images have an angular resolution of 45 arcsec with an average rms of about 0.45 mJy/beam. Full details of the survey can be found in Condon et al. (1998).

3.2 Telescopes

In addition to using pre-existing survey data, I also obtained radio and X-ray images of some of my sources using new targeted follow up observations with the VLA and the XMM telescopes respectively. Within this section I briefly describe these two telescopes. The other main telescope used in producing this thesis, LOFAR, was described in Section 3.1.1. In Sections 3.3 and 3.4 I describe the standard processing techniques I used to reduce the data supplied by the VLA and XMM respectively.
3.2. Telescopes

3.2.1 The Karl G. Jansky Very Large Array

The Karl G. Jansky Very Large Array\(^4\) is a radio interferometer located in New Mexico and consists of twenty-eight 25-metre dishes (see Section 3.3.1 for an overview of radio interferometry). This is an upgraded version of the Very Large Array (also abbreviated as VLA) telescope used to conduct both the FIRST (Section 3.1.4) and NVSS (Section 3.1.5) surveys. The telescopes are arranged in a Y-shape, allowing the VLA to offer relatively good uv-coverage for even short observations.

The telescopes are fixed to rails so that the distances between the baselines can be varied. The VLA offers four standard configurations named A, B, C and D. Configuration A is the largest with a maximum baseline of 36.4 km and a minimum of 0.68 km. Configuration D is the smallest with a maximum baseline of 1.03 km and a minimum of 0.035 km. As a result (unlike LOFAR), it is often necessary to combine images taken using different configurations in order to capture emission on all scales of interest. The VLA operates at frequencies between 58 MHz and 50 GHz which is divided into several ‘bands’. The standard frequency range of each band along with the angular resolution and largest angular scale in each configuration is shown in Table 3.1.

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range / GHz</th>
<th>Resolution / arcsec</th>
<th>LAS / arcsec</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (400cm)</td>
<td>0.058-0.084</td>
<td>24 80 260 850</td>
<td>800 2200 20000 20000</td>
</tr>
<tr>
<td>P (90cm)</td>
<td>0.23-0.47</td>
<td>5.6 18.5 60 200</td>
<td>155 515 4150 4150</td>
</tr>
<tr>
<td>L (20cm)</td>
<td>1.0-2.0</td>
<td>1.3 4.3 14 46</td>
<td>36 120 970 970</td>
</tr>
<tr>
<td>S (13cm)</td>
<td>2.0-4.0</td>
<td>0.65 2.1 7.0 23</td>
<td>18 58 490 490</td>
</tr>
<tr>
<td>C (6cm)</td>
<td>4.0-8.0</td>
<td>0.33 1.0 3.5 12</td>
<td>8.9 29 240 240</td>
</tr>
<tr>
<td>X (3cm)</td>
<td>8.0-12.0</td>
<td>0.20 0.60 2.1 7.2</td>
<td>5.3 17 145 145</td>
</tr>
<tr>
<td>Ku (2cm)</td>
<td>12.0-18.0</td>
<td>0.13 0.42 1.4 4.6</td>
<td>3.6 12 97 97</td>
</tr>
<tr>
<td>K (1.3cm)</td>
<td>18.0-26.5</td>
<td>0.089 0.28 0.95 3.1</td>
<td>2.4 7.9 66 66</td>
</tr>
<tr>
<td>Ka (1cm)</td>
<td>26.5-40.0</td>
<td>0.059 0.19 0.63 2.1</td>
<td>1.6 5.3 44 44</td>
</tr>
<tr>
<td>Q (0.7cm)</td>
<td>40.0-50.0</td>
<td>0.043 0.14 0.47 1.5</td>
<td>1.2 3.9 32 32</td>
</tr>
</tbody>
</table>

Table 3.1: The observing bands/frequencies available at the VLA along with the angular resolutions for each band in each of the four configurations. LAS is the largest angular scale. Data obtained from [https://science.nrao.edu/facilities/vla/docs/manuals/oss/performance/](https://science.nrao.edu/facilities/vla/docs/manuals/oss/performance/)

3.2.2 XMM-Newton

*XMM-Newton*\(^5\) is a space-based X-ray observatory with three telescopes each using a series of mirrors to direct X-rays towards the on-board instruments. The primary instrument consists of three European Photon Imaging Cameras (EPIC) and is sensitive to X-rays between 0.15 and 15 keV providing an angular resolution of 6 arcsec. The system has two MOS-CCD cameras, each with seven chips, each 600×600 pixels in size, with each pixel covering 1.1 arcsec. At the time of writing two of the chips have stopped working in MOS1.

\(^4\)https://public.nrao.edu/telescopes/vla/

\(^5\)https://www.cosmos.esa.int/web/xmm-newton
Chapter 3. Surveys and Data Analysis

The pn-CCD camera has a single chip with twelve embedded CCD’s, each with $64 \times 189$ pixels with each pixel covering 4.1 arcsec.

As well as being sensitive to X-rays, the EPIC CCD’s are also sensitive to infrared, visible and UV light. As a result, each camera has a six-filter wheel three of which, the thick, medium and thin filters, are X-ray transparent filters used to reduce contamination from optically bright sources. Of the remaining three filters, one is fully open and one is fully closed whilst the sixth contains a radioactive source used for calibration.

Though not used in this research, XMM also contains two Reflection Grating Spectrometers (RGS), each attached to one of the telescopes that feed the EPIC-MOS cameras. The RGS can be used to obtain higher resolution spectra from the source than is possible using just the EPIC cameras in the 0.35 to 2.5 keV energy range. The RGS captures 50 per cent of the incoming X-rays with the remaining 50 per cent being caught by the EPIC-MOS cameras. XMM also has an Optical Monitor that is aligned with the X-ray telescopes allowing XMM to provide simultaneous UV/optical and X-ray data.

3.3 Radio Data Reduction and Analysis

The most popular format for radio data, and the only one I used during this project, is the ‘measurement set’ (ms) format. This is used by telescopes including the VLA, LOFAR and ALMA. The ms is a directory structure containing multiple files each of which contains a separate piece of data about the observation. For example, one file will contain the data recorded by each spectral window, whilst another file contains information about where the antenna was pointed. The ms is intended to operate like a relational database so that all the files within the ms can refer to each other.

Since the data I processed was recorded by the VLA I will within this section, where appropriate, refer to VLA-specific data though all such uses are noted. It should however be noted that I did not produce the LoTSS radio images used within this thesis. LOFAR’s wide field of view, the need to account for ionospheric effects important at low frequencies and the petabytes of data produced by LOFAR mean that standard software packages cannot be used and custom routines had to be created to reduce the LOFAR data. As a result, the LoTSS images shown in this thesis were produced by the Surveys team as part of their standard processing (for details see Shimwell et al., 2019; Tasse et al., 2021).

The most common tool used for processing radio data is the Common Astronomy Software Applications\(^6\) (CASA, McMullin et al. 2007) created by the National Radio Astronomy Observatory (NRAO). I used version 5.4.1-32 of CASA to process the VLA radio data. When processing radio data the key stages are:

- Pre-processing
- RFI Flagging
- Calibration

\(^6\text{https://casa.nrao.edu}\)
3.3. Radio Data Reduction and Analysis

- Imaging
- Self-Calibration

The pre-processing stage is discussed in Section 3.3.2 and identifies any corrupted data within the measurement set, typically caused by things like mechanical errors. Radio Frequency Interference (RFI) flagging deals with unwanted signals that are contaminating the data and is discussed in Section 3.3.3. After flagging, the data is adjusted to allow for differences between what is observed by the telescope and the true source signal. These differences can be caused by things such as variations in sensitivity across the receiving bandwidth, differences in sensitivity between the antennas and changes in phase over time. This is the process of calibration and is described in Section 3.3.4. The process of producing images and cleaning them to remove as much of the background noise as possible is described in Section 3.3.5. Finally, the process of self-calibration which aims to improve the image quality by calibrating the data using the images themselves is discussed in Section 3.3.6. More detailed description of all the commands within CASA and the processes used to reduce radio data can be found in the CASA cookbook\(^7\) and in the online CASA tutorials\(^8\), all of which also use VLA data.

3.3.1 Radio Interferometry

Within this thesis, the main survey used to identify the radio emission from radio galaxies is LoTSS which was conducted using LOFAR, a radio interferometer designed and run by ASTRON in the Netherlands. Both LoTSS and LOFAR are described more fully in Section 3.1.1. Within this thesis I also make use of a second radio telescope, the VLA (Section 3.2.1), a radio interferometer based in New Mexico and operated by the National Radio Astronomy Observatory (NRAO). The following description provides an overview of radio interferometry, a more detailed description can be found in Condon & Ransom (2016).

In order to provide an introduction to the benefits and techniques of radio interferometry it is useful to firstly compare with a single-dish telescope. The angular resolution, \(\theta\), of any single-dish radio telescope is determined by the formula:

\[
\theta \approx \frac{\lambda}{d}
\]  

(3.2)

where \(\lambda\) is the wavelength of the incoming radiation and \(d\) is the diameter of the telescope. Therefore, to achieve the 6 arcsec angular resolution of the LoTSS survey, at an equivalent frequency of 150 MHz, a single-dish radio telescope would have to be an unfeasible 69 km in diameter. Instead, interferometers, like LOFAR, combine the signals from multiple, smaller telescopes/antennas to produce images with higher angular resolutions than is possible using single-dish telescopes.

\(^7\)https://casa.nrao.edu/casa_cookbook.pdf
\(^8\)https://casaguides.nrao.edu/index.php/Karl_G._Jansky_VLA_Tutorials
Interferometers consist of multiple receiving antennas (also known as elements) with the distance between any pair of antennas within the array forming a baseline of length $B$, as illustrated in Figure 3.4. Unlike a single-dish telescope, the angular resolution of an interferometer depends upon the baseline length rather than the size of the dish. An interferometer consisting of $N$ antennas will therefore have a total of $N(N - 1)/2$ separate baselines with each baseline having an angular resolution of $\theta = \lambda/b$ (the projected baseline in Figure 3.4). As a result, interferometers ideally have a range of baseline lengths allowing objects to be studied at a range of different spatial scales. For these interferometers, the longest and shortest baselines determine the angular resolution and largest angular scales (respectively) to which an interferometer is sensitive. Regions of emission larger than the largest angular scales are resolved out which is why interferometers are insensitive to radio emission from the cosmic microwave background. This is also why the study of radio galaxies, where the scale of interest goes from microarcseconds at the core to (in some cases) degrees for the lobes, requires a large range of baseline lengths.

For any point source emitting coherent radiation (other than one located directly overhead), the path length between the source and each antenna in the array will be different. Consequently, each antenna will observe the radiation from the source with a different phase offset. Interferometers work by measuring the interference pattern caused when the signals measured by the different antennas within a baseline are combined. Historically these interference patterns were found by adding together the signals from each antenna (e.g. the Michelson interferometer) in a device called the correlator, though all modern correlators do this by multiplying the signals together.
3.3. Radio Data Reduction and Analysis

Using Figure 3.4, which shows a single baseline within an array and defining a vector, $\vec{B}$, which joins the antennas and a unit vector $\vec{s}$ pointing in the direction of the source, the phase delay between the two antennas is $k\vec{B} \cdot \vec{s}$ where $k = 2\pi/\lambda$. As a result, if one antenna receives an input signal $V_1 = V$, the phase delay means the other antenna will receive the signal $V_2 = V \exp^{ik\vec{B} \cdot \vec{s}}$ so that the combined signal is $V^2 \exp^{ik\vec{B} \cdot \vec{s}}$. For an extended source, such as the one shown in Figure 3.4, the signal received can be calculated by treating the source as a series of infinitesimally small point sources. The overall response, $R$, of the interferometer can then be found by summing together the interference patterns generated by each point source giving:

$$R = \int I(\vec{\sigma}) \exp^{ik\vec{B} \cdot (\vec{s} + \vec{\sigma})} d\sigma$$

(3.3)

where $\vec{\sigma}$ defines the on sky direction of the source and $I(\vec{\sigma})$ is the intensity distribution of the sky. Further, defining $\vec{b}$ as the vector representing the projected baseline (see Figure 3.4) and noting the $\vec{B} \cdot \vec{\sigma} = \vec{b} \cdot \vec{\sigma}$, this equation can be rewritten as:

$$R = \exp^{ik\vec{B} \cdot \vec{s}} \int I(\vec{\sigma}) \exp^{ik\vec{b} \cdot \vec{\sigma}} d\sigma$$

(3.4)

Ignoring the first term that contains only known constants and using Cartesian coordinates with normal vectors $\vec{i}$ and $\vec{j}$ to define the two vectors $\vec{\sigma} = x\vec{i} + y\vec{j}$ and $\vec{b} = u\vec{i} + v\vec{j}$, the overall response of an interferometer is normally quoted as:

$$R(u, v) = \int \int I(x, y) \exp^{2\pi i(ux + vy)} dx \; dy$$

(3.5)

This is known as the Van Cittert-Zernike theorem and shows that the telescopes response function is the Fourier transform of the source intensity distribution. In other words, the visibility is the Fourier transform of the sky brightness. Performing the inverse Fourier transform allows the sky intensity map to be obtained from the measured response of the interferometer.

Equation 3.5 shows how the response function depends upon the uv-coordinates of the baseline. To improve the overall quality of the images produced by an interferometer it is therefore necessary to increase the uv-coverage. This can be done by either increasing the number of baselines, thereby increasing the number of Fourier components or by increasing the uv-coverage. The uv-coverage can be increased by either using longer-duration exposures so that the rotation of the Earth causes the baselines to rotate or by using wider-band observations.

However, because it is not practically possible to sample the whole uv-plane, the image (called the dirty image) that is produced by taking the inverse Fourier transform of the interferometers response is actually:

$$I_{dirty}(x, y) = \int \int I(u, v)S(u, v) \exp^{2\pi i(ux + vy)} du \; dv$$

(3.6)
where $S(u, v)$ is the sampling function which is one in those regions that have been sample and zero everywhere else. Defining the dirty beam as the Fourier transform of the sampling function:

$$B(x, y) = \int \int S(u, v) \exp^{2\pi i (ux + vy)} \, du \, dv \quad (3.7)$$

it is possible to calculate the dirty beam accurately since we know the locations of the antennas. The convolution theorem then tells us that the dirty image can be expressed as the convolution of the ‘true’ sky image with the dirty beam:

$$I_{\text{dirty}}(x, y) = I(x, y) \ast B(x, y) \quad (3.8)$$

where $\ast$ is the convolution operator.

Therefore, once an observation is complete, in order to produce a final ‘clean’ image any unwanted human-made radio signals (also known as radio frequency interference or RFI) must be removed, the data must be calibrated to account for the effects of both the telescope and the atmosphere upon the strength of the detected signal and then cleaned to remove the effects of the dirty beam. In order to produce a realistic looking image and to acknowledge the angular resolution limit, the cleaned image is then convolved with a ‘clean’ beam, which is usually the main lobe of the dirty beam. The process of producing radio images from observational data is described more fully in Section 3.3.

### 3.3.1.1 Radio Interferometry at Low Frequencies

As described above radio interferometry relies on measuring the interference pattern generated when the signals recorded by two separate antennas are combined. One of the issues that all radio telescopes have to account for during calibration is changes in the phase of the signal caused by the atmosphere. This is a particular problem at low frequency where the signal is strongly affected by the Earth’s ionosphere which can cause rapid and substantial changes in the signal received.

This is less of a problem for telescopes with short baselines and a narrow field of view as it can be assumed that all the detected radiation will have passed through nearly identical atmospheric conditions so that any phase changes affect all signals simultaneously. However, for LOFAR this is a particular problem as it has both long international baselines and a wide field of view. These effects can result in (time varying) positional shifts or distorted sources.

Though the details are beyond the scope of this thesis, LOFAR deals with these effects using a combination of direction independent and direction dependent calibration techniques. The LOFAR pipeline first uses direction independent calibration to account for those effects that are not affected by ionospheric changes, such as the time delay between receiving antennas, differences in sensitivity etc. Using these results a model of the sky map is constructed which is then broken into several sections, known as facets, with each facet covering a different area of sky. Each facet is then processed separately using direction dependent calibration to allow for any phase shifts caused by the atmosphere. The
final calibration solutions are then combined and applied to the entire data set to produce the final images. For further details see Shimwell et al. (2019); Tasse et al. (2021).

3.3.2 Pre-processing

Any bad data that is known to exist must be identified so that it is not included in any subsequent processing. The process of identifying bad data within the measurement set is known as ‘flagging’. However, it should be noted that the process of flagging does not delete any data, it merely labels it as bad so that, if necessary, flags can be reset and the data can be recovered. Therefore, CASA supplies the flagmanager tool that saves all the flags at any given time allowing users to rollback to an earlier save point if necessary.

The primary source of information about any known bad data is the observers log, although in most cases the necessary information can also be derived from the measurement set. The most common issues are discussed in the following subsections.

3.3.2.1 Equipment Malfunction

If any equipment malfunctioned during the observation then any data recorded by that equipment is unreliable and must be flagged. The duration of any malfunctions is reported in the operator’s log.

3.3.2.2 Antenna Shadowing

Shadowing occurs when one of the radio dishes is obscuring the view of another radio dish within the array. This is typically a problem when the dishes are located close to each other and the target source is at low altitude. For the VLA this occurs at elevations below 40 degrees and is most problematic in the D-configuration when the antennas are closest together. Typically, problems associated with shadowing get worse as the source elevation decreases. CASA’s flagdata command can identify and flag any instances where the amount of shadowing is above a user-defined tolerance.

3.3.2.3 Quacking

Whenever the antennas move it can take them a moment at the beginning of each observation to settle down. It is therefore common practice to remove the data at the start of each scan. This process is known as quacking and removes a user defined time period from the start of each scan.

3.3.2.4 Zero-Amplitudes

Occasionally radio telescopes output zero-valued data. These data must also be flagged.
3.3.3 RFI Flagging

Whilst the previous section dealt with data that was known to be bad at the time the observation was made, this section deals with RFI, contaminating data that can only be identified as bad by studying the output from the telescope.

There are multiple potential sources of RFI including natural phenomena such as lightning or solar flares, as well as human-made electrical equipment such as mobile telephones, car ignitions and even microwave ovens (Petroff et al., 2015)! To help with identifying RFI, the VLA publish a list of common sources that affect the equipment along with the frequencies at which they are observed. It is important to remove RFI as otherwise it can dramatically affect the quality of the images produced and result in dubious scientific data.

Of particular relevance to RFI flagging is how CASA divides the observing bandwidth into spectral windows with each spectral window being subdivided into a number of channels, each with its own unique frequency. Depending on the nature of the RFI, it may affect only a few (narrow-band RFI) or multiple channels (broad-band RFI) and may be either short or long-lived.

In the following subsections I describe the Hanning smoothing algorithm (Section 3.3.3.1) along with the two algorithms available in CASA for automatically identifying and flagging RFI (Section 3.3.3.2). I also describe the tools available for manual data flagging (Section 3.3.3.3).

3.3.3.1 Hanning Smoothing

Whilst strictly not a flagging algorithm, Hanning smoothing is used to reduce the impact of the Gibbs phenomenon (also known as Gibbs ringing). The Gibbs phenomenon occurs where strong pieces of narrow-band RFI cause unwanted fluctuations in the surrounding channels. Hanning smoothing works by smoothing the channels using a weighted average with the central channel having a weight of 0.5 and the two surrounding channels having a weight of 0.25 each.

Though not relevant to this research, Hanning smoothing does reduce the spectral resolution of the data by a factor of two so that it may not always be appropriate. If running Hanning smoothing, it is best to run it before the automatic flagging algorithms described below as otherwise the automatic flagging algorithms may flag data from the surrounding channels that Hanning smoothing could have recovered. Since this process smooths all the visibility columns making flagging impossible, it instead outputs a new measurement set so that, if necessary, the original data can be recovered from the original measurement set.

9https://science.nrao.edu/facilities/vlba/observing/rfi
3.3.3.2 Automatic Flagging

CASA supplies two functions that can automatically identify and flag RFI: TFCROP and RFLAG. Both functions work by dividing the observation into a series of data chunks and then iterating through the chunks. By default each data chunk is a single scan of an object though this can be changed by the user. Both TFCROP and RFLAG can either flag data automatically or present it to the user for manual inspection before committing.

In summary, TFCROP works by firstly averaging the data within each chunk over time before calculating the best fit bandpass. It then flags data that is more than a user-defined number of standard deviations away from the best fit. Secondly, TFCROP averages each data chunk with respect to frequency before finding the best fit polynomial to the time series which it again uses to find outliers. The TFCROP algorithm can identify short duration RFI and time persistent narrow-band RFI.

Unlike TFCROP, the RFLAG algorithm requires an initial bandpass calibration of the data (see Section 3.3.4). It is important to note that this bandpass calibration is done purely to allow RFLAG to run smoothly, the final bandpass calibration is done after flagging. Care must be taken when running RFLAG as it can mistake spectral lines for noise. In summary, RFLAG works by firstly iterating through each channel within the data chunk. For each channel it performs a sliding window time analysis, calculating the RMS for each time window before finding the median RMS across all the time windows. It then flags any time chunks that deviate significantly from the average. Secondly, RFLAG iterates through each timestamp within the data chunk, again calculating the average rms across all the channels. It then flags those channels that deviate significantly from the average. The RFLAG algorithm can identify strong peaks in RFI as well as noisy RFI.

3.3.3.3 Manual Flagging

It is also possible to visually inspect the data, identifying any RFI. The examples given here of how to manually search for RFI are based on the VLA tutorials\textsuperscript{10}. In practice the large amounts of data to be viewed mean that, when manually searching for RFI, it is best to average the data shown using either time and/or frequency before examining it for any potential RFI. If RFI is identified it is then possible to drill down into the data to identify the exact time and frequency of the RFI.

Narrow-band RFI can be identified using CASA’s PLOTMS to plot amplitude vs frequency and can be seen as a sudden change in signal amplitude affecting a limited range of spectral windows/channels. Overhead satellites would be an example of a source of narrow-band RFI (Figure 3.5). Once identified the duration of the interference can be found by plotting amplitude vs time for the affected channel(s). To see if all or only some of the antennas are affected the amplitude of the signal in the plots can be subdivided by antenna. Once identified, the appropriate pieces of RFI can then be flagged.

\textsuperscript{10}https://casaguides.nrao.edu/index.php/Karl_G._Jansky_VLA_Tutorials
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Figure 3.5: Narrow band RFI caused by the three satellites that form the Sirius digital radio system. Observed using the VLA B configuration during the S-band observation of ILT J112543.06+553112.4 (see Chapter 5).

Intermittent RFI can be identified using CASA’s plotms to plot amplitude vs time for any given spectral windows. Intermittent RFI is seen as a sudden and temporary change in amplitude. Similar to narrow-band RFI, once a piece of intermittent RFI is identified it is often necessary to plot amplitude vs frequency for the time period of the RFI so that the affected channels can be identified. As above, the strengths of the signal in these plots can be subdivided by antenna to see if all or only some of the antennas are affected. Once identified, the appropriate pieces of RFI can be manually flagged.

3.3.4 Calibration

There are several non-astrophysical effects that may affect the detected signal. For example, ground-based interferometers have to consider the atmosphere which can cause a shift in the observed phase of a source. Also, radio interferometers like the VLA and LOFAR consist of multiple antennas all observing the same source simultaneously. Unfortunately, no two antennas are ever exactly identical and there will always be small differences in sensitivity between antennas.

Calibration is the process of adjusting the observed visibilities to account for all the processes that may have altered the signal so that the true source visibility can be reconstructed. For each effect we wish to calibrate, a calibration table must be generated. These calibration tables are then applied, in order, allowing the true source visibilities to be reconstructed.
Within this section I describe the types of calibration source used (Section 3.3.4.1) and the calibration procedure adopted (Section 3.3.4.2). The procedure presented here follows the methods described in the online VLA tutorial\footnote{https://casaguides.nrao.edu/index.php?title=VLA_Radio_galaxy_3C_129:_P-band_continuum_tutorial-CASA5.5.0}. The self-calibration process is conducted after the imaging process and is discussed separately in Section 3.3.5.

### 3.3.4.1 Calibration Sources

In order to calibrate an observation, two types of calibration source are needed: the primary (also called the flux density) and secondary (also called gain or complex gain). The general strategy is to firstly calibrate the primary, then to use these solutions to calibrate the secondaries before applying the solutions for the secondary calibrators to the target sources. As a result, in addition to the target sources, every observation must include one source that is to be used as the primary calibrator and one or more sources that are to be used as secondary calibrators.

Within an observation, each secondary calibrator is associated with one or more nearby target sources as seen on the plane of the sky. The similar line of sight to the sources allows the assumption that any environmental changes affect both sources equally. Under this assumption, the calibration solutions derived for the secondary can also be applied to the target source. Observations with multiple targets are therefore likely to require multiple secondary calibrators.

The primary calibrator must be a source of known, constant flux density and phase that is used to calibrate the telescope and scale the flux densities observed allowing different observations to be compared. The primary calibrator will typically be observed once at either the beginning or end of the observation. There are four primary calibrators recommended for use in VLA observations.

The secondary calibrators should have an intrinsic phase that can be considered constant over the course of a single observation. The flux densities of secondary calibrators may vary, typically over timescales of months to years preventing them from also being used as primary calibrators.

The same secondary calibrator must be observed both before and after the scan of its associated target as well as, depending upon the length of time the target is being observed, at repeated intervals during the scan. The time period between each successive observation of the secondary must be short enough to ensure that the atmosphere can be assumed to have remained constant. If the primary calibrator is sufficiently close to the target it can also be used as a secondary calibrator.

### 3.3.4.2 Calibration Procedure

Some of the effects for which we wish to calibrate exist independently of the sources observed. For example, antenna positions, variations in the total electron content (TEC) of
the atmosphere and requantizer gains. The calibration tables for each of these effects can therefore be generated first and can be applied to both primary and secondary calibrators.

Using the source-independent calibration tables and the known properties of the primary calibrator, the next stage is to derive a bandpass solution which describes the sensitivity of the instrument as a function of frequency. The bandpass solution is assumed to be constant throughout the duration of an observation. Having derived a bandpass solution, it is then necessary to generate phase and gain solutions for the primary calibrator. These tables allow for any environmental changes that occurred during the observation. Combining all the calibration tables, it is then possible to fully calibrate the primary calibrator.

Having calibrated the primary, it is then necessary to find phase and gain solutions for the secondary calibrators. Using the known flux density of the primary these solutions are scaled to ensure a reliable flux density scale. These solutions are then applied to the secondaries so that they are fully calibrated. Finally, the calibration solution from the appropriate secondary calibrator is applied to each target source at which point each source is ready for imaging (see Section 3.3.5).

### 3.3.5 Imaging

Once the data has been calibrated images can be produced. Performing an inverse Fourier transform on the raw data produces an image known as the ‘dirty image’. This image is a convolution of the ‘true’ image and the telescopes beam. To remove the effects of the beam, deconvolution algorithms are applied to create a ‘clean image’. Conceptually cleaning can be pictured as peeling off consecutive layers from the dirty image and deconvolving them until only the background remains. The layers removed are then combined with the remaining background to form the clean image.

In CASA cleaning is done using the CLEAN algorithm which supplies several deconvolution algorithms. Within this thesis I use the multiscale algorithm (Cornwell, 2008) which is intended for use with extended objects, such as radio galaxies. The multiscale algorithm assumes the detected radio emission comes from a range of angular scales. In summary, it works by finding the location of the peak radio emission within the dirty image and then selecting the spatial scale from amongst a user-defined list that best describes the extended emission centred at that point. It then convolves the selected spatial scale with the dirty beam, multiplies the result by a factor known as the loop gain and then subtracts the result from the dirty image, the result is known as the residual image. This process is repeated until some user-defined stopping factor is reached such as when the peak emission value in the dirty image reaches a threshold, or after a fixed number of iterations. Finally, the subtracted values are convolved with the clean beam and combined with both each other and with the residual image to create the clean image.

During the imaging process it is also possible to weight the visibilities, allowing users to highlight structures on different scales. For example, uniform weighting emphasises the longer baseline data and is used to highlight small-scale structure. However, the disadvantage of uniform weighting is a poorer signal to noise. Conversely a natural weighting
emphasises shorter baselines resulting in better sensitivity but poorer angular resolution. In between these two extremes is Briggs weighting where the user can determine the relative weightings of the short and long baselines.

### 3.3.6 Self-calibration

The primary and secondary calibrators are generally observed at different times to the sources. This can result in small differences between the phase and amplitude solutions derived using the secondary calibrators and those actually experienced when observing the source. Self-calibration is used to adjust for these effects.\(^{12}\)

Self-calibration involves firstly cleaning an image as described in Section 3.3.5. The resulting image is then used as a model from which self-calibration solutions are derived. The self-calibration solutions are then applied to the image which is then cleaned further. In general, this involves applying phase-only self-calibration solutions until there is no significant improvement in image quality. If any calibration errors remain this can be followed by applying phase and amplitude self-calibration corrections.

As with standard calibration, self-calibration assumes the model is perfect, it is therefore necessary to be able to derive an accurate model of the source from the images. For sources with low signal to noise this will not generally be possible. As a result, the CASA team recommend that the data should satisfy the following requirement in order to attempt self-calibration.\(^{13}\):

\[
\frac{S_{\text{peak}}}{\text{RMS}} > 3\sqrt{N} - 3\sqrt{\frac{t_{\text{int}}}{t_{\text{solint}}}} \tag{3.9}
\]

where \(S_{\text{peak}}\) is the peak flux density, \(N\) is the number of antennas, \(t_{\text{int}}\) is the total on source integration time and \(t_{\text{solint}}\) is the solution interval length.

### 3.3.7 Radio Flux Density Measurements

Having produced radio images, the first task is normally to use those images to measure the flux density of the source as well as the background noise.

The background noise can be found in CASA using the `imstat` tool. Whilst this can be done from the command line by calling `imstat` directly and passing in the coordinates of the region to be analysed, it is far easier to use the graphical `viewer` tool supplied with CASA. Within `viewer` it is normally best to manually select a region that surrounds the target source and that is free from any bright background sources as it is then possible to more accurately measure the levels of noise affecting the target. Having selected a region of the image, `viewer` can then be used to display statistical information about the region as shown in Figure 3.6. This information includes the rms noise of the region.

In order to find the flux density and, if required, the peak brightness of a source it is first necessary to specify the source region. In CASA, this can be done manually in `viewer` by selecting the source emission region and, as above, using the statistical information supplied

\(^{12}\)https://casaguides.nrao.edu/index.php/VLA_Self-calibration_Tutorial-CASA5.7.0

\(^{13}\)https://casaguides.nrao.edu/index.php/Self-Calibration_Template
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Figure 3.6: An example of using CASA’s viewer tool to measure noise. The panel on the right gives statistical information about the region highlighted in pink, including the rms noise, peak brightness and flux density.

to find the flux density and peak brightness. The main drawback with this method is the need to manually define the region to be analysed which, whilst possible for small numbers of sources, is not practical when dealing with large samples. Further, different users will inevitably define different source regions, although it is to be expected that the results found by professional users would not differ significantly.

The CASA alternative to manually defining source regions is to use the imfit function which automatically finds the peak emission, fits a single Gaussian to it and then produces the same statistical information as imstat. This has the benefit of reproducibility, however, unlike point sources radio galaxies are generally not Gaussian and so information derived from a single Gaussian fit may not accurately represent the source. For those sources with multiple, identifiable components this can be partially mitigated by manually identifying each separate sub-component and then iterating through each identified region calling imfit. However, this again requires manual interaction to identify each separate sub-component plus, for many radio galaxies, it is either not practical or possible to define them as a set of separate Gaussians. Therefore, for the images I processed within this thesis I manually identify the emission regions.

As mentioned in Section 3.1.1, LoTSS is the primary survey used to identify the radio galaxies studied within this thesis. However, within this thesis I typically use images processed by the improved DR2 pipeline (Tasse et al., 2021) for which catalogue information was not, at the time, available. Therefore, when studying individual sources in detail (see Chapters 5 and 6), rather than relying on the LoTSS DR1 catalogue values, which can underestimate the sizes and flux densities of the smaller sources I am studying (Mingo et al., 2019), I instead used values manually derived from the LoTSS DR2 Flexible Image
Transport System (FITS) format images. The complexity and size of the data produced by LOFAR means that proprietary software is used to reduce the data and produce the final FITS images so that the file format information required by CASA is not available. Whilst it is possible to upload FITS images into CASA, I preferred the flexibility offered by the RADIOFLUX\textsuperscript{14} DS9 add-on developed by M. Hardcastle.

Similar to how VIEWER works, RADIOFLUX uses DS9 (see Section 3.5) to allow users to define which regions are to be analysed before finding the flux densities for those regions. The RADIOFLUX tool is also slightly more flexible than VIEWER as it allows source and background noise regions to be analysed simultaneously and, although not used in this thesis, can automatically subtract the background noise from the target source. RADIOFLUX also offers a Python interface (see Section 3.5) that I used to transfer the results directly into the FITS catalogue I created for my sources.

### 3.3.8 Integrated Spectral Indices

As described in Section 1.3, the spectral index relates the source flux density at a given frequency, $S_\nu$, with the frequency, $\nu$. The integrated spectral index (i.e. the spectral index calculated using the integral of the radio flux density observed across the entire source) is often used as an indicator of the bulk properties of a source and is used in classifications of compact radio sources (e.g. O’Dea, 1998) and remnants (e.g. Brienza et al., 2017). By using the integrated radio flux density measurements taken by different observations at different known frequencies I wrote a piece of software to calculate the integrated spectral index.

### 3.3.9 Magnetic Field Strengths and Internal Energies

In order to understand the energetic impact of radio galaxies it is important to consider the energy stored within the radio lobes. It is also important to derive the magnetic field strengths within the lobes (which contribute to the internal energy) when producing spectral ageing models of radio sources (Section 3.3.11). Within my work I found both of these values using a Python (see Section 3.5) version of the SYNCH\textsuperscript{15} code of M. Hardcastle, first used in Hardcastle et al. (1998), hereafter referred to as PySYNCH. Whilst PySYNCH offers a range of functionality to describe synchrotron-based radio emission, I only describe the functionality I used within this thesis.

Using the observed radio flux density measurements, the magnetic field strength is normally estimated under either equipartition or minimum energy assumptions (see Section 1.3.1). PySYNCH works by assuming all the observed flux density comes from either an ellipsoid, cylinder or a sphere of user-defined size. Within this thesis (unless specified otherwise) I assume the emitting region is ellipsoid in shape, using DS9 (see Section 3.5) to measure the size of the region. PySYNCH supports both power-law and broken power-law energy distributions with the user specifying the injection index, the range of Lorentz indices:

\begin{align*}
\text{Energie}_\text{internal} &= \frac{1}{2} \mu_0 B^2 R^3 \\
\mu_0 &= \text{magnetic permeability of vacuum} \\
B &= \text{magnetic field strength} \\
E &= \text{energy stored} \\
R &= \text{radius of the emitting region}
\end{align*}

\textsuperscript{14}Available at \url{https://www.extragalactic.info/~mjh/radio-flux.html}

\textsuperscript{15}\url{https://github.com/mhardcastle/pysynch}
values for the electrons and, if necessary, the break frequency. PySYNCH also supports different assumptions about the relative contribution of non-radiating particles to the total energy budget. Using these values PySYNCH adjusts the magnetic field to find either the minimum or equipartition value that gives the observed emissivity. For individual sources, the assumptions used to obtain more realistic values, are described in the text (Section 6.4). Having calculated the magnetic field strength it is possible to calculate both the magnetic and particle energy densities (see Section 1.3.1) which combine to give the internal energy density.

### 3.3.10 Spectral Index Maps

Within this thesis I use several radio maps of the same source, each taken at a different frequency, to produce spectral index maps. I created spectral index maps using the Broadband Radio Astronomy Tools (BRATS) written by J. Harwood. BRATS allows for detailed spectral analysis of radio images, providing a suite of model fitting, visualisation and statistical tools. A full description of all the functionality offered by BRATS is contained in the online cookbook\(^ {16}\). Within this section I describe how I used BRATS to produce spectral index maps.

The spectral index maps produced by BRATS show the spectral index for each pixel allowing users to quickly see any variation in spectral index across the source. To do this BRATS requires that the maps being combined are the same size, have identical beam sizes and have pixels representing identical spatial scales.

To match the beam sizes the higher angular resolution image(s) must be smoothed so that they match the lower angular resolution images. I did this by firstly writing some Python code to calculate the size of the Gaussian needed for the smoothing and then using CASA’s `imsmooth` function to perform the actual smoothing. To match the pixel spatial scales, I used CASA’s `imregrid` function. In order to retain as much information as possible I re-gridded the LOFAR image to match the smaller pixel sizes of the VLA image.

Following the methodology of Harwood et al. (2013), once the radio maps have the same beam sizes and spatial scales they can be loaded into BRATS using the `load` command. In order to be sure that only radio emission from the source is analysed, BRATS allows users to set a minimum signal to noise level using the `sigma` command. Below this level any radio emission is ignored. Throughout this thesis I set BRATS to use a source detection threshold of three sigma.

When analysing data BRATS defaults to using VLA calibration errors, therefore whenever a radio map from any other telescope is used it is necessary to manually set the calibration errors for that map using the `fluxcalerror` command. Within this thesis I combined radio maps taken with both the VLA and LOFAR, I therefore set the flux density calibration errors for the LOFAR radio maps to 0.2 (Shimwell et al., 2019).

\(^{16}\) [http://www.askanastronomer.co.uk/brats/downloads/bratscookbook.pdf](http://www.askanastronomer.co.uk/brats/downloads/bratscookbook.pdf)
Finally, BRATS can be instructed to find which regions to include in the spectral index maps by running the `setregions` command. Spectral index maps and the associated error maps can then be produced using the `specindex` and `specindexerrors` commands respectively. An example of a spectral index map produced by BRATS is shown in Figure 3.7.

### 3.3.11 Spectral Age Maps

As well as producing spectral index maps, BRATS can also be used to produce spectral age maps (see Section 1.3.2). In this section I describe the functionality within BRATS that I used to produce spectral age maps.

Spectral ageing maps are produced based on spectral index maps such as those described in Section 3.3.10. Therefore, before BRATS can produce spectral ageing maps, each of the radio maps used must have the same beam size and each pixel must represent the same spatial scale. This process was described in the previous section.

Along with the radio images, the other inputs required for spectral age modelling are the magnetic field strength and the injection index. I found the equipartition magnetic field strengths using PySYNCH as described in Section 3.3.9.

The injection index is a measure of the spectral slope at the time when the synchrotron-emitting electrons are accelerated (see Section 1.3). As a result, the observed spectral index at the assumed site of particle acceleration is often used as the injection index. However, as described in Harwood et al. (2013), convolution with the beam may introduce systematic errors into the observed spectral slopes. I therefore used BRATS `findinject` command to find the injection index.
Figure 3.8: An example of a spectral ageing map produced by BRATS. The beam is shown as the blue circle in the bottom right of the image. This image is of ILT J112543.06+552112.4 (see Section 5.7.3).

FINDINJECT command works by iterating through a range of injection index values. For each injection index, it uses a discrete set of user-defined ages to generate a series of spectral ageing models. Grouping the pixels into regions to give the required signal to noise ratio, BRATS then finds the best fitting spectral age model for each region before calculating the $\chi^2$ across the whole source. FINDINJECT returns the injection index with the lowest $\chi^2$ value.

After finding the injection index, BRATS can be used to fit spectral ageing models to each region in the image. Each region’s age is then determined by the best-fitting model. BRATS supports three spectral ageing models, the Jaffe-Parole (JP, Jaffe & Perola, 1973), the Kardashev-Pacholczyk (KP, Kardashev, 1962; Pacholczyk, 1970) and the Tribble models (Tribble, 1993). Each of these models produces a spectral ageing map of the source such as the one shown in Figure 3.8. BRATS uses the standard $\chi^2$ test to report the goodness of fit for the source as a whole as well as for the individual regions.

All three models used by BRATS are single injection models which assume that the electrons responsible for the radio emission at any given source location were all injected at the same time. In summary, the main difference between them is that the KP model assumes the electrons are at a constant pitch angle throughout the source whilst the JP model allows a varying pitch angle. Unlike the KP and JP models, which assume a fixed magnetic field strength, the Tribble model allows a (Gaussian) variable magnetic field strength across the source. Within this thesis I use the JP model as it is believed to provide a realistic model of the conditions in radio galaxies (Mahatma et al., 2020), though it should be noted that at low frequencies the results of the models do not differ significantly (Biava et al., 2021).
3.4 X-ray Data Reduction and Analysis

X-ray astronomy is often described as being photon-starved and as a result all X-ray telescopes detect individual photons with each detection being called an ‘event’. The time, the position where the photon was detected and energy of each event is recorded in an events file which is supplied to users in FITS format.

Along with the events files, users are also supplied with various housekeeping files that describe the status of the detector and satellite at the time of the observation. For data supplied by XMM, the housekeeping and events files are collectively known as the Observation Data Files (ODF). The exact process for reducing X-ray data varies depending on which telescope recorded the information. The X-ray data used within this thesis was recorded by XMM and so, whilst the general principles are common to reducing all X-ray data, the processes described below are specific to XMM.

In Section 3.4.1, I describe the pre-processing steps necessary to gather all the information supplied by XMM together. In Sections 3.4.2, 3.4.3 and 3.4.4, I describe how to use the events files output by the pre-processing stage to produce images, spectra and surface brightness profiles respectively. The data reduction and analysis described in this Section uses a combination of three tools:

- Version 18.0 of the Science Analysis System (SAS)\textsuperscript{17} tool supplied by ESA for processing XMM data
- Version 6.27 of the FTOOLS\textsuperscript{18} package supplied by NASA’s High Energy Astrophysics Science Archive Research Center (HEASARC)
- Version 4.12 of the Chandra Interactive Analysis Operations (CIAO) supplied by NASA’s Chandra X-ray Center (CXC)\textsuperscript{19}

3.4.1 Pre-processing

The pre-processing stage takes the XMM data and converts it into one events file per camera containing details of the energies, times and locations of each photon received. These events files can then be used in subsequent processing. I performed all pre-processing tasks using SAS.

3.4.1.1 Calibration

The efficiency of the pixels varies across the CCD chips on-board XMM. They also vary with temperature and time. These effects are described fully in the XMM handbook\textsuperscript{20}. Therefore, before any data processing can take place, these effects must be calibrated for.

\textsuperscript{17}https://www.cosmos.esa.int/web/xmm-newton/download-and-install-sas
\textsuperscript{18}https://heasarc.gsfc.nasa.gov/ftools/
\textsuperscript{19}https://cxc.cfa.harvard.edu/ciao/
\textsuperscript{20}https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/
The XMM team continually update the calibration files and so the first stage is to download the most up-to-date version from the European Space Astronomy Centre (ESAC) website\textsuperscript{21}. Once downloaded, the data can then be processed by calling the tasks cf
build, which, based on the date of the observation, selects the appropriate calibration data, odfinest which applies the calibration and housekeeping data to the observation producing what is called the ODF summary file and attthkgem which stores the attitude information of the spacecraft during the observation. Finally, the emchain task is run to produce event files for each of the MOS cameras and epchain is run to produce the events file for the pn camera. Each file contains a list of events and associated data quality flags which identify multiple events in the same region that are likely due to particle background or flares.

3.4.1.2 Background Flares

Processing each event file separately and using data from the entire field of view, any background flares that occurred during the observation will be visible as sudden increases in the lightcurve (for a description of the X-ray background see Lumb et al., 2002; Carter & Read, 2007; Bulbul et al., 2020). However, since some sources are intrinsically variable, it may not be immediately obvious whether an increase in the lightcurve is due to source variability, in which case it should be kept, or whether it is due to background flares and should be rejected. Fortunately, the extended radio galaxy components studied in this thesis vary slowly and can be considered constant over human lifetimes. As a result, any short-term variability is unrelated to the source. Also, unlike AGN sources, X-ray background flares are visible across the entire energy range to which XMM is sensitive. Therefore, lightcurves are constructed for each camera using the top end of the energy ranges where AGNs sources shouldn’t be visible (10 - 12 keV range for the MOS cameras and 12 - 14 keV range for the pn camera). I used the xmmselect tool to generate lightcurves, such as the example shown in Figure 3.9, for each camera within the corresponding energy range.

Using the lightcurves produced an approximate base count-rate can be seen. Since the signal varies around this baseline flaring events are considered to occur when the count-rate is significantly higher than the baseline. For example, in Figure 3.9 the baseline count-rate is approximately 70 counts per time interval and time periods where the count-rate moves above $\sim 100$ can be considered as flaring events. Those time periods where flaring does not occur are the Good Time Intervals (GTI).

Whilst flaring will typically affect large numbers of pixels within the same region, photons from AGN sources will normally only register in one pixel and possibly the neighbouring pixels so that it is possible to identify likely flaring events based on the pattern of pixels affected. XMM defines several standard patterns for how pixels can be affected\textsuperscript{22}. I only accepted standard patterns 12 or less for the MOS cameras (i.e. where the photon

\textsuperscript{21}https://www.cosmos.esa.int/web/xmm-newton/current-calibration-files
\textsuperscript{22}https://xmm-tools.cosmos.esa.int/external/sas/current/doc/emevents/node4.html
3.4. X-ray Data Reduction and Analysis

Figure 3.9: Lightcurve taken by the MOS1 camera during the observation of ILT J120645.20+484451.1. Several flares can be seen during the observation at times where the count rate is above 100.

Affected a 2 square region of pixels or less) and a pattern of 4 or less from the pn camera (i.e. only single or double events).

Using the lightcurves produced I then used the `tabgtigen` function to calculate the good time intervals for each camera. I then used `evselect` to filter each of the events files, selecting only those events within the good time intervals, that satisfied the desired pattern and that were not flagged by the system as being potential contaminants. This produced clean events files for each of the three cameras.

3.4.1.3 Vignetting

Vignetting causes images to be brighter in the centre than at the edges. To compensate for this, I used the `evigweight` tool for each of the three events files causing each event to be weighted by a value that depends upon its pixel location.

3.4.1.4 Out of Time Events

Out Of Time (OOT) events are events that are recorded whilst the detector is reading the CCD resulting in an incorrect detector coordinate in the y-direction. This affects about 6.3 per cent of all events detected with the pn-camera and 0.35 per cent for MOS (in full frame mode). Whilst the OOT rate for MOS is sufficiently low it can be ignored, for the pn-camera they can cause artificial broadening of spectral features. It may therefore also be necessary to subtract OOT events from the pn-camera data before processing the data. OOT event files are constructed from the raw data using the `epchain` command. This
takes the observed data and assigns random y-coordinates to each event. The OOT data is then scaled by a factor of 0.063 to account for the number of events typically affected before being subtracted from the pn-camera data as though it were a background as described in the following sections.

3.4.1.5 Pile Up

Pile up occurs when two photons strike the same or neighbouring pixels during a single read-out cycle so that the two events are treated as a single event with a total energy equal to the sum of the two. Pile up must be considered when a source is sufficiently bright that the possibility of pile up is non-negligible. Pile up results in hardening of the spectrum and a reduced count rate. The MOS camera is more sensitive to pile up than the pn camera for the same source flux density. Single events (PATTERN=0) are typically less affected by pile up.

The SAS tool epatplot shows the number of observed counts for single, double and single+double events as a function of energy along with expected models. If the observations diverge from the model, then it is likely there is significant pile up. If present, pile up is normally dealt with by filtering out the bright cores of sources where pile up is most likely to originate from.

3.4.2 Producing Images

Using the images from the pre-processing stage I used evselect to filter the energy range to the 0.5 - 5 keV band used within this thesis. Using this energy range prevents high energy emission from the nucleus dominating the images so that the morphology and size of the radio lobes can be seen more clearly (see Section 1.1). I then combined the data from the events files for each of the three separate XMM cameras into a single image as discussed in Section 3.4.2.1. So that the source of interest can be viewed more clearly it is sometimes necessary to remove background sources from an image. This, along with image smoothing is discussed in Section 3.4.2.2. Within this thesis, the X-ray images produced are used to identify and locate any X-ray structures. Any flux density measurements, spectral analysis or surface brightness profiles are then taken using the events files.

3.4.2.1 Combining Data to make Images

To account for differences in the sensitivity of the three cameras, the events files for each separate camera must be weighted during the combination process. This avoids the more sensitive pn camera dominating the image, reducing the prominence of the chip gaps in the pn camera and allowing data from the MOS cameras to effectively fill in the gaps. This is done by finding a region within each separate band-filtered events file that is clear of bright background sources and then finding the number of counts within the region. Using DS9 to view the events files collapses the file along the energy axis allowing me to see the total energy received in each pixel. In practice, since the number of pixels is very large,
3.4. X-ray Data Reduction and Analysis

I used DS9’s binning tool to bin the pixels into groups of 64 in both X and Y directions allowing me to view the events file in image form. I also used DS9’s scale function to view the energy in log space and make the individual sources easier to see. It was then possible to identify the desired region and using the FUNTOOLS tool within DS9 to get the number of counts. The relative count-rate per pixel of each camera is then determined according to the formula:

$$\text{Count rate per pixel} = \frac{C}{Rt}$$

(3.10)

where $C$ is the total number of counts observed, $R$ is the region size and the livetime, $t$, is the total amount of time for which the camera was active. Finally, the weighting of each MOS camera can be calculated by dividing the count-rate per pixel of the pn camera by the count-rate per pixel of the MOS camera.

I then used the perl script xmmimage.pl, written by J. Croston to apply these weightings to the band-filtered events files and combine them into a single FITS-format image. In summary, this script uses the EVSELECT tool to create FITS images for each of the cameras. The weightings described above are then used to scale the two MOS camera images using the FARITH tool before adding each of the images together to produce a combined image. Using the EEXPMAP tool it then creates the exposure maps which details the sensitivity of each pixel for each of the three cameras. Once again using FARITH, these exposure maps are then added together creating a combined exposure map for all three cameras. To correct for individual pixel variation, the combined image is then divided by the combined exposure map to produce the final image.

3.4.2.2 Post Processing of Images

Though not needed for the images I produced in this thesis, background sources can be removed from an image by using DS9 to selecting regions where there are no sources and then using the DMFILTH tool to effectively cut and paste these regions over the background sources.

As mentioned in Section 3.4, X-ray astronomy is ‘photon-starved’ with the result that images often look patchy. Assuming that the emitting sources are in reality smooth in nature it is therefore common practice to use a Gaussian to smooth the image allowing individual blocks of emission to be merged together. I used the tool ACONVOLVE to smooth images. This also means that different size Gaussian kernels can be used to highlight structure on different scales. All X-ray images should indicate the size of Gaussian used to smooth the image.

Since within this work I am also interested in any relationship between the observed X-ray and radio emission I also overlay radio contours on top of the X-ray images. I do this using code I wrote in Python using the APLpy library (see Section 3.5).
3.4.3 Spectra

In order to produce reliable spectra it is important to subtract any background contaminants. There are three potential sources of background X-rays (Carter & Read, 2007):

- The extragalactic background
- The local bubble
- The Milky Way

The extragalactic X-ray background is believed to due to AGN activity and emits with a power law spectrum of approximately 1.42 (Lumb et al., 2002). The local bubble is a low-density region of space surrounding the sun caused by hot X-ray emitting gas that is itself the result of past supernova activity. This region has a thermal spectrum of $\sim 0.75$ keV. The Milky Way also emits X-rays, possibly the result of X-ray binaries, and also has a thermal spectrum of $\sim 0.25$ keV.

In addition to the X-ray background there is also contamination from the instrument itself, commonly known as the 'particle background'. This contamination is measured using closed filter-wheel backgrounds that are taken when the telescope filter is closed providing high signal-to-noise information about particle and instrumental background as a function of spatial position.

To account for these contaminants both source and background regions must be defined with the background as close as possible to the source so that it can be assumed to have the same level of contamination (Section 3.4.3.1). Having defined these regions, the spectral data for each region is then extracted (Section 3.4.3.2) and, if necessary adjusted to allow for Out Of Time (OOT) events (Section 3.4.3.3). The data is then grouped into bins so that reliable spectral models can be made (Section 3.4.3.4).

Once the data is grouped, the simplest way of performing background subtraction is to simply scale and subtract the background region from the source region. This is known as single subtraction and is described in Section 3.4.3.5. However, since closed filter-wheel backgrounds account for the instrumental background separately from the galactic and extragalactic backgrounds, it is possible to subtract each background component separately using a process called double background subtraction (e.g. Croston et al., 2008a). This process uses closed filter files that have been filtered and weighted in the same way as the source data sets and have had their coordinates transformed to match the source using the ATTCALC task. Double subtraction is described in Section 3.4.3.6 and can be used to produce more accurate models of the source. The process of generating spectral models from the background subtracted data is described in Section 3.4.3.7. Spectral fitting using both single and double background subtraction techniques was done using version 12.11 of HEASARC’s XSPEC package\textsuperscript{23}.

\textsuperscript{23}https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/
3.4.3.1 Identifying Regions

The first stage is to define both the source and local background regions. In the case of the background region this is typically an annulus centred on the host. The inner ring of the annulus should be far enough away from the host that any flux from the source can be ignored whilst the outer ring should be close enough that the background contamination can be considered representative. For my sources I did this using DS9 (for an example see Figure 6.3).

It is also necessary to identify and exclude from analysis the chip gaps as well as any known bad pixels as within these regions there will not be any background emission that could affect the spectra. I overlaid DS9 region files supplied by J. Ineson, on top of the event files to select areas to be excluded. In addition, it is also necessary to identify and exclude individual X-ray sources that impinge upon either the source or local background regions and could contaminate the spectra. These can be detected automatically using tools such as EDETECT_CHAIN, though for smaller sky areas it may be more efficient to manually identify sources. The regions associated with the individual background X-ray sources and the chip gaps collectively form the exclusion regions.

3.4.3.2 Extracting Region Data

After identifying the source and local background regions as well as the exclusion regions, the events files must be filtered to include only events from the region of interest. I used the SPECTRA_CDBL.PL perl script written by J. Croston which, in summary, uses the SAS EVSELECT command to filter and collapse the vignetting-corrected events file along the time axis to extract the spectral data into a standard format FITS file. This script filters the data so that it only includes those events that fall within the corresponding region and outside of any exclusion regions. The SPECTRA_CDBL.PL script also uses the PI values when constructing spectra which are the numeric values used to represent the electric pulse height recorded by the instrument adjusted to account for variations in sensitivity across the instrument.

Each camera is processed individually, with the SPECTRA_CDBL.PL script using the events file to produce spectra for both the source and local background regions. It also uses the closed filter-wheel events file to produce additional spectra for the source and local background regions so that, if desired, double background subtraction can be performed (Section 3.4.3.6). However, before the closed filter-wheel data can be subtracted from the corresponding region in the observational data it must be weighted to account for the different exposure times. To do this SPECTRA_CDBL.PL uses the MATHPHA command within FTOOLS to weight the closed filter spectra by a user-defined amount with the resulting spectra being saved in a separate file. I calculated the weightings as described below.
Calculating Weightings for Closed Filter-Wheel Data

In order to calculate reliable weightings for each camera energy ranges where there is no emission from the sources should be used. This is typically the 10 - 12 and 12 - 14 keV bands for the MOS and pn cameras respectively. Therefore, using the methods described in Section 3.4.2, images are produced in these energy bands for each closed filter file.

To calculate the weightings I followed the methodology of Croston et al. (2008a) and defined a large circular region in the centre of the image that was covered by all three cameras. Then, after excluding the chip gaps and bad pixels, I used the FUNTOOLS function within DS9 to calculate the number of counts recorded by each camera in both the observation and closed filter images. I then found the count-rate for each image by dividing the number of counts by the duration of the observation. Finally, I obtained the background subtraction rate for each camera by dividing the count-rate from the observational data by the count-rate from the closed-filter background giving the final weighting value for each camera.

3.4.3.3 Subtracting Out of Time Events

The SPECTRA_CDBL.PL script has an option to simultaneously generate two spectral files from the OOT events file, one for the source and the other for the local background region. To allow for OOT events these files are scaled before being subtracted from the corresponding region using the FCALC tool. The resulting OOT-subtracted spectral files for the pn-camera can then be treated in the same way as the spectral files for the MOS cameras.

3.4.3.4 Grouping Channels

When a spectral model is generated (Section 3.4.3.7) it predicts how many photons (also referred to as counts) will be observed in each of the energy channels used by the telescope. During the fitting, the model parameters are varied to obtain the best possible fit. The most common test used to determine which set of parameters provides the best fit to the observational data, and the one I use in this thesis, is the \( \chi^2 \) test.

However, in order to apply the \( \chi^2 \) test every energy channel should contain at least 15, preferably 20 counts. As a result, if any given channel has fewer counts than a user-defined minimum, then that channel is grouped with consecutive neighbouring channels until the total number of counts in the group exceeds the minimum. This group is then treated as a single block throughout the model fitting process.

The most common way to group channels is using the GRPPHA command within FTOOLS which uses the observed data and tests each channel to see if it contains the, user-defined, minimum number of counts. If not, it combines the channel with each subsequent channel until the minimum number is reached. However, this process is done using the source region only and so does not take into account the effects of background subtraction. Therefore, a group that initially contained more than 20 counts may have fewer
counts after background subtraction is taken into account making it necessary to test the
number of counts in each group after background subtraction but before fitting a model
spectrum and, if necessary, regrouping the channels. To simplify this process, I used the
fungroup.c code written by J. Croston and M. Hardcastle which groups the channels as
described above after allowing for the effects of background subtraction.

### 3.4.3.5 Single Background Subtraction

As already mentioned, the X-ray emission seen in the local background region is assumed
to be representative of the level of background emission seen in the source region. This is
likely to be a reasonable assumption where the source and background regions are close on
the detector. In this situation it is therefore possible, after allowing for differences in region
sizes, to simply subtract the observed local background from the observed source region
to obtain a ‘clean’ events list that can then be used to model the spectra. This is single
background subtraction (more commonly referred to as simply background subtraction)
and is performed automatically by the tool I used, xspec, whenever it is supplied with
separate source and background regions.

### 3.4.3.6 Double Background Subtraction

For larger sources, like radio galaxies, it will often be the case that the local and background
regions are far away from each other on the detector. As a result, the spatial response of
the telescope, in particular because the X-ray background is vignetted whilst the particle
background is not, mean that the background region may no longer be representative of
the level of background emission seen in the source region. In these circumstances more
accurate spectra can be obtained using the double background subtraction techniques
described here.

Using double background subtraction, the closed filter files are used to subtract the
particle and instrumental background from both the source and local background regions.
The local background and source regions are then modelled separately with the model
from the local background being scaled and subtracted from the local source region. In
this subsection I summarise the method for performing double background subtraction
that is more fully described in Croston et al. (2008a).

Firstly, I subtracted the closed filter background region data from the equivalent re-
gion in the observational data file. The resulting data is then modelled in xspec (Sec-
tion 3.4.3.7). Since the closed filter data is calculated based on very long observing times,
it very accurately reflects the instrumental and particle background. This background
component can be the dominant spectral component at high energies and must therefore
be removed in order to model the radio galaxy. The background spectral model produced
therefore represents the local, Milky Way and extra-galactic X-ray background.

Since the source and background regions are different sizes it is expected that the larger
area would detect more background X-ray photons. As a result, the background model
must be scaled so as to represent the assumed level of background contamination in the
source region. The scaling ratio is derived from the size of each region output by the perl script, SPECTRA_CDBL.PL, used to generate the spectral files.

Finally, the closed-filter file source region is subtracted from the equivalent region in the observational data file with the resulting data being a combination of (a) the source and (b) the local, Milky Way and extra-galactic X-ray background. The local and extra-galactic component is modelled by scaling the background model based on the relative region sizes and treating it as a fixed component. This allows the source component to be modelled separately in XSPEC (Section 3.4.3.7). Therefore, at the cost of additional processing steps, the double background subtraction technique results in a more reliable source spectra with reduced uncertainties.

3.4.3.7 Fitting Model Spectra

In order to calculate model spectra both source and background event files are needed so that background events can be subtracted before fitting a spectrum. For XMM, each of the three cameras has its own associated set of events files. Whilst it is possible to process each camera separately, I chose to process the data from each camera simultaneously so that XSPEC fits the same model (albeit with different normalisation parameters) to each of the three data sets.

Some channels are flagged as bad either by the telescope due to technical problems or by the grouping process described above. After loading the data it is therefore standard to ignore these channels using the IGNORE BAD command. It is then possible to enter a model that the user wishes to test, along with the initial parameters. The system will then adjust the parameters so as to minimise the difference between the model and the observed values. As already mentioned, I used the standard $\chi^2$ test to measure the goodness of fit.

XSPEC provides several model components that can be combined by the user to produce an accurate model spectrum. Within this work I use the phabs photoelectric absorption, the po power law and the apec model components. The phabs model is a multiplicative component that is applied to other model components and is used within this work to account for galactic absorption of X-rays. The phabs component requires the column density of neutral hydrogen within the Milky Way that lies along the line of sight. It then uses an exponential model to calculate the amount of energy from the source that would be absorbed as a function of energy. The po model is an additive component that can be added to other components and is used to model emission from non-thermal synchrotron sources. It assumes the X-ray flux produced at any given energy, $A(E)$, is given by the relationship $A(E) \propto KE^{-\alpha}$ where $K$ is a constant of proportionality, $E$ is energy and $\alpha$ is the photon index.

Finally, the apec (astrophysical plasma emission code, Smith et al. 2001) model is used to model both continuum and line emission from an optically-thin collisionally excited plasma such as the diffuse ISM of galaxies. The continuum emission is assumed to come primarily from the bremsstrahlung emission (Section 1.4) of electrons with a Maxwell-Boltzmann distribution of energies whilst the line emission is calculated primarily from
3.4. X-ray Data Reduction and Analysis

Radiative transitions by combining the electron number density with the abundance of metallic elements in the emitting region.

As the temperature of the plasma changes, so does both the peak of the Maxwell-Boltzmann distribution and the emission line strengths. The \textit{apec} model takes both into account when estimating temperature. Within this thesis I use the \textit{apec} model to estimate the temperature of the hot ISM surrounding the galaxies and to model the expected emission for any jet-driven shocks.

3.4.4 Spatial Analysis

X-ray surface brightness profiles give the count rate per unit area as a function of the radial distance from the source. Since the emissivity depends upon the density of the emitting plasma (Section 1.4) and, since density and pressure are related, it is possible to use surface brightness profiles to infer the pressure of the surrounding environment. Within this section I follow the methodology of Birkinshaw & Worrall (1993), which has been adapted to use Markov Chain Monte Carlo (MCMC) methods to explore the parameter space, describing how to generate surface brightness profiles and fit models to them.

In order to generate surface brightness profiles, I used the following suite of surface brightness analysis and modelling utilities written by J. Croston and M. Hardcastle. An overview of each of these tools is given within the following text.

- \texttt{FUNPROFILE.C}
- \texttt{FUNINPUT.C}
- \texttt{NEWXMMPSF.C}
- \texttt{XMMPROFS.PL}
- \texttt{PROPLOT.C}
- \texttt{MCMC.BETA}
- \texttt{MCMCNDERR} executable
- \texttt{PRESSURES\_RR} executable

3.4.4.1 Surface Brightness Profiles

As above, it is first necessary to calibrate the data, to remove any flares from the data, to correct for vignetting and, if desired, to allow for OOT events. These processes are described in Section 3.4.1.

I used the \texttt{FUNPROFILE.C} code to generate the radial surface brightness data for each camera. This script takes the user-supplied location of the source centre and, after allowing for any regions to exclude, it uses the user-supplied list of annuli to calculate the surface brightness for each respective annulus. In order to keep the local background as spatially close as possible to the source I used the outermost annulus as the local background.
The **funprofile.c** code can perform either single or double background subtraction (see Sections 3.4.3.5 and 3.4.3.6), to perform single background subtraction the background count rate is scaled, based on annulus area, and then subtracted from each of the other annuli. For double background subtraction, the number of counts in each region (including the background) is calculated using the closed filter files. These values are then subtracted from the number of counts calculated for the identical region using the source data. Finally, the background region is subtracted using the same process as single background subtraction.

To aid with generating the input to the **funprofile.c** code, I used the **funinput.c** code which takes the event files for each camera, along with a user-supplied list of exclusion regions (e.g. background X-ray sources) and finds the central pixel of the source (the centroid). This script also adds the locations of the chip gaps to the exclusion regions. The list of exclusion regions was generated using DS9 as described in Section 3.4.3.1.

The output from **funprofile.c** lists the number of counts present in each of the user-supplied annuli. In order to obtain a good surface brightness profile there should be at least 20 counts in each annulus. I therefore iteratively adapted the number and size of annuli before re-running the two scripts until this had been achieved. In practice the pn camera has more counts and so it is this camera that I ensured had 20 counts in each annulus. As a result, the profiles from the other two cameras are not as good. Instead, the data from the two MOS cameras was used to supplement the data from the pn-camera and refine the surface brightness profile.

Before combining the data to produce a single surface brightness profile, I modelled the PSF for each of the three cameras so that, when modelling the surface brightness profile, the contribution of the PSF could be modelled separately from the underlying profile. To do this I used the **newxmmpsf.c** code which requires the user to supply the off-axis angle of the target source. In summary, this code uses information from the calibration files to calculate the energy-dependent PSF as a function of radius from the source centre. Moving radially outwards from the source position, it calculates the effect of the PSF at each CCF-defined energy range which is then weighted based on the relative importance of the energy range to the overall observation. The weighted values are then summed giving the overall effect of the PSF to the observation.

After calculating the PSF for each camera, I used **xmmprofs.pl** to combine the data into a single, combined surface brightness profile. This script also weights the PSF calculated for each camera according to the relative observing times before combining them into a single combined PSF. I used **proplot.c** to plot the combined profile information as a graph. A sample output from proplot is shown in Figure 3.10.

### 3.4.4.2 Model Fitting

As described in Section 1.4.1, the density and pressure profiles for group/cluster environments can be derived from the X-ray surface brightness profile. This subsection describes this process.
3.4. X-ray Data Reduction and Analysis

Figure 3.10: The combined surface brightness plot generated for the LoTSS source ILT J120645.20+484451.1 between 0.5 and 5 keV.

Assuming a spherically symmetric, isothermal environment, it is possible to model both the surface brightness and density profiles using a beta model (e.g. Cavaliere & Fusco-Femiano, 1976; Croston et al., 2008a; Ineson et al., 2013). The profiles are defined as:

\[
\rho(r) = \rho_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-\frac{3\beta}{2}}
\]

(3.11)

\[
S(R) = S_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta+0.5}
\]

(3.12)

where \(\rho(r)\) is the density at radius \(r\), \(S(R)\) is the surface brightness at projected radius \(R\), \(\rho_0\) and \(S_0\) are normalising constants, \(r_c\) is a characteristic radius and \(\beta\) defines the slope of the profile. It is worth noting that for more complex and/or deep X-ray observations more sophisticated models are needed (Birkinshaw & Worrall, 1993; Arnaud et al., 2010), however for the objects considered in this thesis the beta model gives a sufficiently good fit.

Since the emissivity is related to density and temperature, these two equations are related by (Birkinshaw & Worrall, 1993):

\[
S(R) \propto \frac{\Lambda(E, T)}{4\pi d\Omega D_L^2} \int \rho(r)^2 dV
\]

(3.13)
where $\Lambda(E,T)$ is the emissivity function at energy $E$ of a gas with temperature $T$, $d\Omega$ is the solid angle subtended by the source and $D_L$ is the luminosity distance. The proportionality arises from the need to adjust this equation to take account of the sensitivity of the instrument and because of the assumed proportionality in the number density of protons and electrons.

To fit Equation 3.12 to the observed surface brightness profile I used the Markov Chain Monte Carlo (MCMC) code MCMC.BETA. This program convolves the beta profile with the PSF of the telescope, adjusting the parameters to obtain the best fit. It outputs a list of all the beta model parameters tested along with the likelihood of each. I then passed these results to the MCMCNDERR executable code which outputs both the maximum likelihood parameter values (i.e. those that best fit the data) as well as the Bayesian estimate (the most often visited values) plus the one sigma errors.

I then used the PRESSURES_RR executable which takes a user-defined radius and temperature and, along with the output from MCMC.BETA calculates the density (and errors) at that radius according to Equation 3.11. Since Equation 1.27 relates the pressure, temperature and density in an ideal gas, by also supplying PRESSURES_RR with the temperature of the environment (see Section 3.4.3.7) the code can output the pressure (and errors) at any given radius. Using the results across a range of radii it is therefore possible to construct both density and pressure profiles of the environment.

3.5 Other Tools

During my research I used several well-known third-party tools, the general purpose of each is briefly described below. The main tools used include:

- Topcat
- SDSS Skyserver
- Python

The Tool for OPerations on Catalogues and Tables (TOPCAT)\textsuperscript{24} is designed to allow easy editing and visualisation of tables (Taylor, 2005). Throughout my research I used TOPCAT to query and combine data from the surveys used (see Section 3.1) as well as using it to catalogue the results of my own observational data.

The SDSS Skyserver provides a suite of tools for accessing images and catalogue data from the Sloan Digital Sky Survey (SDSS). Though superseded by more current releases, I used Data Release 14 throughout this research which was, at the start of this project, the most up to date version\textsuperscript{25} (Abolfathi et al., 2018).

Within the SDSS Skyserver, the two main tools I used were the navigation tool and casjobs. The navigate tool provides access to the optical images taken by SDSS as well

\textsuperscript{24}http://www.star.bris.ac.uk/~mbt/topcat/
\textsuperscript{25}https://skyserver.sdss.org/dr14/
3.6. Summary

as providing links to the related entries in the common astronomical databases NED, SIMBAD and ADS. The casjobs tool uses the Structured Query Language (SQL) to provide a command-line based interface to the catalogue data.

Python\textsuperscript{26} is a high-level, object-oriented programming language that has become the \textit{de facto} standard within the astronomical community. There are several programming interfaces available for Python, I used the Spyder\textsuperscript{27} graphical user interface. I used version 3.6 of Python, which was the most up to date version at the start of the project. Since version 3 of Python is not backwards compatible and since many third-party pieces of software were written using version 2, I have had to do a small amount of work using version 2.7.14. There are multiple Python libraries available, including many that are specifically intended for astronomers. The most common libraries used within my work are:

- numpy\textsuperscript{28}
- astropy\textsuperscript{29}
- aplpy\textsuperscript{30}
- math\textsuperscript{31}
- matplotlib\textsuperscript{32}

These libraries provide support for high-level mathematical, astronomical and graph plotting functionality.

3.6 Summary

Within this chapter I have described the LoTSS survey used within this thesis to identify GSJ as well as the SDSS, NVSS, FIRST and WISE surveys used to provide ancillary data. I have described the VLA and \textit{XMM-Newton} telescopes used to observe a subset of GSJ and gather data about them. I have also described the data reduction techniques used to produce images and perform data analysis on both radio and X-ray data. In subsequent chapters I use survey data to identify a population of GSJ within the local Universe and analyse the radio and X-ray follow-up data obtained for a sub-sample of sources, using the results to answer the scientific questions raised in Section 2.6.

\textsuperscript{26}https://www.python.org
\textsuperscript{27}https://www.spyder-ide.org
\textsuperscript{28}https://numpy.org
\textsuperscript{29}https://www.astropy.org
\textsuperscript{30}https://aplpy.github.io
\textsuperscript{31}https://docs.python.org/3/library/math.html
\textsuperscript{32}https://matplotlib.org
Chapter 4

Properties of Galaxy Scale Jets and their hosts

The contents of this chapter have been published in Monthly Notices of the Royal Astronomical Society as Webster et al. (2021a).

4.1 Introduction

As described in Section 2.1, in order to reproduce a realistic-looking Universe, with galaxy numbers, sizes and distributions similar to those observed, simulations such as Illustris (Weinberger et al., 2018) and EAGLE (Schaye et al., 2015) must include some form of feedback that restricts the star formation rate (SFR). Active Galactic Nuclei (AGN) feedback from radio jets is one form of feedback where, as described in Section 2.4, the energy transported by the jets ultimately restricts the rate at which material is accreted back into the galaxy where it can form stars and ultimately fuel the AGN itself.

The majority of the observational evidence for feedback from radio galaxies is associated with large jets of \( \sim 100 - 1000 \) kpc (e.g. Mullin et al., 2008), capable of carrying energy far into the surrounding intracluster medium. However, as described in Section 2.5, feedback from physically small sources, such as GSJ, may be having a significant, and hitherto largely overlooked, effect upon galactic evolution. Consequently there are a growing number of studies looking into the effects of feedback from compact radio sources such as parsec-scale Gigahertz-Peaked Spectrum (GPS) and Compact Steep Spectrum (CSS) sources a few kpc in size (e.g. Bicknell et al., 2018; Tadhunter, 2016b), along with some studies of intermediate-size radio structures (e.g. Jarvis et al., 2019; Jimenez-Gallardo et al., 2019).

The advent of telescopes such as the International LOw Frequency ARray (LOFAR) Telescope (Section 3.1.1), with its combination of high sensitivity to both compact and extended emission (Shimwell et al., 2017), allows for the systematic identification of GSJ, whose radio jet sizes are of a similar scale to that of the host galaxy, together with the study of the potential effects these sources can have upon their host environments.

At present very little is known about the galaxies that host GSJ (Section 2.5). The majority of previously discovered GSJ are hosted by ellipticals but a small number are hosted by spiral galaxies (e.g. Hota & Saikia, 2006; Gallimore et al., 2006; Croston et al.,
Chapter 4. Properties of Galaxy Scale Jets and their hosts

2008b; Mingo et al., 2012). It is therefore presently unclear whether these smaller jets form part of the evolutionary sequence of a ‘typical’ radio-galaxy or a separate population. It is also not yet known how GSJ and the population of large-scale double-lobed radio galaxies hosted by spiral galaxies, the so-called spiral DRAGNs (Mulcahy et al., 2016), may be related.

In order to investigate the importance of GSJ in shaping galaxy evolution I used the first data release (DR1) of the LOFAR Two Metre Sky Survey (LoTSS; Shimwell et al., 2019; Williams et al., 2019) to find a sample that is large enough to draw statistical conclusions. As described in Section 3.1.1, LoTSS DR1 contains over 300,000 sources making it impossible to visually search through the catalogue for GSJ. Within this chapter I describe the system I devised that uses the host and radio morphology to reduce the number of potential sources to more manageable numbers and how I then used a combination of size criteria, existing AGN/star formation separation methods, and visual inspection to identify the GSJ sample used within this thesis. These methods have the advantage that they can be easily implemented in future catalogue releases.

Using the catalogue of GSJ I found, the remainder of this chapter aims to:

• examine the radio and host properties of the GSJ as well as the environments in which they are typically found.

• describe the selection effects that influence the sample.

• describe how common GSJ are when compared to both the overall population of galaxies as well as the wider population of AGN.

• look at the potential impact of GSJ upon their hosts.

• place my results within the wider context of galaxy evolution.

4.2 Sample Selection

Before I could study the properties of GSJ I firstly had to create a selection methodology capable of generating a large, reliable sample of radio galaxies with galaxy-scale jets. I aimed to do this in an automated way using readily available catalogue data, so that in the future my methodology can be applied to larger sky areas. In Section 4.2.3 I describe my method for generating an automated sample of GSJ with Table 4.1 showing the sample size at each step of the process. In order to validate my method and ensure that my selection criteria is not introducing any biases (e.g. against a particular type of host), I also generated a smaller, visually selected, clean sample that I used for more detailed investigations of the properties and impact of GSJ. My approach to selecting this clean sample is discussed in Section 4.2.4.

The starting point for my sample selection was the 231,716 sources from the LoTSS DR1 value-added catalogue with an optically identified host (see Section 3.1.1). As explained in Sections 4.2.2 and 4.2.3, I also made use of the Hardcastle et al. (2019) (hereafter H19)
4.2. Sample Selection

<table>
<thead>
<tr>
<th>Selection step</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR1 sample with optical IDs</td>
<td>231,716</td>
</tr>
<tr>
<td>Resolved with LoMorph size measurement</td>
<td>15,472</td>
</tr>
<tr>
<td>Total length less than 80 kpc</td>
<td>2,987</td>
</tr>
<tr>
<td>Jet:Galaxy ratio in range 2-5</td>
<td>454</td>
</tr>
<tr>
<td>Automatic Sample (AS)</td>
<td>192 (167(s), 25(p))</td>
</tr>
<tr>
<td>Visual Sample (VS)</td>
<td>52 (48(s), 4(p))</td>
</tr>
<tr>
<td>Total Sample (TS)</td>
<td>195 (170(s), 25(p))</td>
</tr>
</tbody>
</table>

Table 4.1: The size of the sample at each step of the selection process. The AS, VS and TS show how many of each sample have spectroscopic (s) and how many have only photometric (p) measurements.

catalogue of 23,444 radio-loud AGN which were selected from the DR1 catalogue based on a combination of radio excess, spectroscopic and infrared colour diagnostics. However, to avoid biases from pre-judging the likely host-galaxy colours and emission line properties of GSJ, where the radio excess may be relatively low, I did not use the AGN catalogue as my initial starting point. My selection criteria, which are explained in detail below and summarized in Table 4.1, include (i) improved size estimation and a size cut-off, (ii) a threshold in the ratio of radio to host galaxy size, as measured along the jet axis, (iii) AGN/star formation separation based on the catalogue of H19.

4.2.1 Size Selection

The LoTSS catalogue includes source size estimates determined by the Python Blob Detector and Source Finder pyBDSF (Mohan & Rafferty, 2015). However, these elliptical regions were obtained through Gaussian approximations to the source extent, and sometimes do not accurately represent the shape or size of the radio emission. For small objects that may have complex brightness distributions, which are of particular interest for this thesis, pyBDSF tends to underestimate their true size (see Mingo et al., 2019, for details). I therefore used part of the LoMorph code of Mingo et al. (2019) to measure the total extent of the radio emission above a threshold set at 5 times the RMS noise. I started by eliminating unresolved sources using the criteria of Shimwell et al. (2019) and rejected those sources with a measured flux density below 2 mJy as too faint to measure. This left 25,128 sources, of which 15,472 had sufficient flux density for LoMorph to determine an accurate size.

I then applied a size cut-off to select only those objects consistent with being GSJs, i.e. with radio emission on scales comparable to their host. Typical large elliptical galaxies have half-light radii up to approximately 20 kpc, though the full extent of the galaxy will be significantly larger (Forbes et al., 2017). I therefore chose to exclude all sources with a total extent greater than 80 kpc, in other words larger than twice the typical galaxy half-light diameter. Projection effects may mean that some of these sources are in fact larger than 80 kpc, however, since the inclinations are unknown, I made no allowance for this. Applying this size criterion left 2,987 sources.
4.2.2 Jet:Galaxy Ratio

To further refine the sample to include only objects with jet-related emission on a similar scale to the host, I divided the size of the radio emission by the optical size of the host to get the jet:galaxy ratio for all 2,987 sources. Since radio lobes can be found at a wide range of angles relative to the host’s major axis (e.g. Gallimore et al., 2006), for example see Figure 4.8, I measured the size of the host along a line defined by the position angle of the radio emission (taken from LoMorph). This avoided prejudicing the selection against highly elongated hosts.

The host galaxy sizes were obtained from the SDSS DR14 catalogue (Abolfathi et al., 2018). A further 52 sources were excluded due to not having an SDSS match within 3 arcsec. The catalogued i-band de Vaucouleurs radius and ellipticity were used to determine the host size along the axis of the radio emission, except where the i-band radius was $> 1.5\sigma$ from the mean across all five bands, in which case the band closest to the mean was used.

The size of the host measured along the axis of the radio emission is given by the formula:

$$ r = \frac{ab}{\sqrt{b^2 \cos^2 \theta + a^2 \sin^2 \theta}} $$  (4.1)

where $a$ and $b$ are the semi-major and semi-minor axes respectively, $r$ is the distance to the edge of the ellipse and $\theta$ is the angle of the jet to the semi-major axis as measured in the plane of the sky.

The LoMorph-measured radio size was divided by the host size to obtain the jet:galaxy ratio for each object. Figure 4.1 shows the distribution of jet:galaxy ratio vs the angular size of the radio emission (taken from LoMorph), where a jet:galaxy ratio $> 1$ indicates emission extending beyond the host galaxy.

I used visual inspection to determine suitable automated thresholds for the jet:galaxy ratio as well as for the angular size of the radio emission. At angular sizes less than twice the LoTSS resolution (12 arcsec), it became difficult to be certain that any extended structure is genuine and not due to calibration uncertainties, and so I eliminated all sources with an angular size $< 12$ arcsec, leaving 2,105 sources.

A lower threshold in jet:galaxy ratio was needed to reduce contamination from star-forming galaxies, while an upper threshold was needed to exclude objects where the majority of energy must be deposited at a large distance from the host. Figure 4.2 gives an example of a galaxy whose radio-emission appears to be due to star formation. To determine the lower threshold, I examined the subset of candidates with jet:galaxy ratios between 1 and 3. In the range 1 - 2, the radio emission from 35 of 76 candidates has the appearance of a star-forming galaxy, whereas in the range 2 - 3, only 4 of 58 candidates appear dominated by radio emission from star formation.

I adopted a lower jet:galaxy ratio cut-off of 2, as the best compromise to enable fully automated selection without a high level of contamination. Unfortunately, this unavoidably excluded the smallest GSJs whose jets are embedded within the central regions of the galaxy. Future higher angular resolution studies (e.g. future releases of LoTSS using the
4.2. Sample Selection

Figure 4.1: Plot of the total angular size of the radio emission versus the jet:galaxy ratio. The vertical lines and horizontal lines represent the jet:galaxy ratios and angular sizes used to reduce the size of the candidate sample. The objects within the LoTSS DR1 sample and the subset identified as radio-loud AGN by H19 are shown.

international baselines), should be able to resolve jet-related structures on sub-galactic scales, allowing these sources to be identified using my methods.

A further compromise was needed in choosing an upper threshold for the jet:galaxy ratio. Sources such as spirals and highly elongated ellipticals with jets closer in projection to the minor axis could have high jet:galaxy ratios whilst still having jets that are small enough to be directly influencing the host’s evolution (e.g. in a way similar to the jet-induced turbulence and outflowing ionised gas bubbles within the host’s ISM proposed by Jarvis et al. (2019). A jet:galaxy ratio of 5 was chosen as the upper cut-off.

Applying the lower and upper jet:galaxy ratio cut-offs created a candidate sample of 454 sources. This sample was used to define an automatically selected sample, and a smaller, visually selected sample as described below.

4.2.3 The Automatically Selected Sample

Of the 454 candidate sources obtained by applying the size and jet:galaxy ratio thresholds, the 192 that are classified as AGN by H19 form the ‘Automated Sample’ (AS). Applying the techniques described in Section 2.2, the methods of H19 provide a straightforward automated method to avoid significant contamination by radio sources dominated by star formation. Based on a visual check of the AS there does appear to be some low level of contamination, with about 2 per cent potentially being misclassified star-forming galaxies (discussed further in Section 4.4.2.1), plus an additional 6 per cent where the radio emission seen by LOFAR from the GSJ is potentially blended with another source. For these sources
Figure 4.2: Image of ILT J111056.42+532312.2. An example of an AS galaxy whose radio emission appears to be related to star formation rather than AGN activity. The LOFAR beam is shown in the bottom left and a scale bar in the bottom right. Radio contours are shown at $3 \times 2^n$ times the local RMS where $n \in \{0,0.5,1.0,...\}$. 
it is possible that the catalogued radio flux densities may be slightly too high. It is also possible that some of the catalogued flux densities include an element of non-jetted AGN-related radio emission. However, within this chapter I make no modifications to catalogued flux density values.

As with any flux-density limited survey, some of the sources may have additional extended emission below the surface brightness limitations of LoTSS. Any such sources would be correspondingly larger and might therefore not qualify as GSJ according to my criteria. Even if this were the case for some of the sources, at least some of the energy associated with the emission seen by LoTSS must be transferred locally, so that these sources could still be having an impact on galaxy scales. In the future, higher-sensitivity LoTSS deep fields data could give an estimate of what percentage of GSJ have faint extended emission on larger scales. As above, no allowances are made for these potential contaminants. A sample of AS sources is shown in Figure 4.3.

### 4.2.4 The Visually Selected Sample

In order to verify the selection methods used to find the AS, I visually inspected all 454 candidate sources (Section 4.2.2) to identify those sources with unambiguous jetted structure. Unlike the AS which aims to be as complete as possible, this sample, referred to as the ‘Visual Sample’ (VS), is intended to be as clean as possible. The VS can therefore also be used for detailed investigations and for optimising follow-up observations. When inspecting the sources, I applied the following criteria:

- Sources with a clear double-lobed morphology were always considered as GSJ. For example, in the leftmost column of Figure 4.4 the GSJ (top) has two clearly defined, roughly circular, radio features at the opposite ends of the jet. In contrast the rejected source (bottom) has quite diffuse emission with two poorly defined circular features buried within the radio emission. Whilst these features may be due to AGN activity it could also be caused by star-forming regions within the host galaxy.

- The shape of the radio emission. Sources with circular emission or a brightness distribution closely matching that of the host could easily be caused by star-forming activities and were rejected. In contrast strongly elliptical radio structures with large amounts of flux and aspect ratios greater than about two were typically considered to be GSJ. For example, the middle column of Figure 4.4 shows a GSJ source (top) with much more pronounced ellipticity than the rejected source (bottom).

- Sources where there was a strong asymmetry in the radio emission on either side of the host. Whilst most of these are still likely to be jetted sources, the asymmetry may indicate that either the jets are inclined at a significant angle compared to the plane of the sky so that the source is not a true GSJ, that some of the observed flux is attributable to a secondary background source or that the host has been incorrectly identified. For example, in the rightmost column of Figure 4.4 the radio emission on
Figure 4.3: Sample of AS sources. Images show LOFAR contours in gold overlaid on an i-band SDSS image in colour. The red cross indicates the location of the LoTSS DR1 host. The LOFAR beam is shown in the bottom left and a scale bar in the bottom right. Radio contours are shown at $3 \times 2^n$ times the local RMS where $n \in \{0, 0.5, 1.0, \ldots \}$. 
4.3 Sources in the VS but not the AS

either side of the GSJ (top) is very similar whilst the radio emission on one side of
the rejected source (bottom) is much longer than the other suggesting that the jets
may be bent/inclined towards us and that this is not a true GSJ.

This inspection resulted in a sample of 52 GSJ which form the VS, of which 49 are also
in the AS. The VS sources are shown in Figure 4.5. The three sources in the VS that are not
in the AS are ILT J112543.06+553112.4 (hereafter ILTJ112543), ILT J121847.41+520128.4
(hereafter ILTJ121847) and ILT J123158.50+462509.9. The first two appear to be spiral
hosted radio galaxies which, due to their unusual hosts were not included in the H19
catalogue, whilst the third is an elliptical host with an unusually low luminosity compared
to its star formation rate. All three sources are discussed in detail in Section 4.3. It
therefore appears that when combined with my selection techniques, the methods of H19
can be used to find GSJ, although these three sources indicate that this will exclude a
small percentage (∼1.5 per cent of the sample) of genuine GSJ.

The 143 sources in the AS that are not in the VS predominantly have either one-sided
or round-ish emission. Whilst the radio excess used by H19 strongly suggests that these
sources are radio galaxies, their morphology is too ambiguous to be included in the visual
sample.

In order to have as large a sample as possible, all the unique sources in both the AS
and VS are combined to produce the 195 sources that form the ‘Total Sample’ (TS). A
summary of the three samples is given in Table 4.1 and the two-sided jet lengths for the
AS, VS and TS are shown in Figure 4.6.

4.3 Sources in the VS but not the AS

As described in Section 4.2, three sources were included in the VS that were not found in
the AS. In this section all three sources are considered individually.

4.3.1 ILT J112543.06+553112.4

The image of ILTJ112543 shown in Figure 4.7 leaves no doubt that the observed emission
is AGN related. The image shows two FRII-like lobes of roughly equivalent fluxes that are
visible in both FIRST and LOFAR. In addition, the sensitivity and angular resolution of
LOFAR shows the jetted radio emission joining these two structures. Whilst the identified
host clearly lies closer to the north west lobe such an asymmetry is not unusual in radio
galaxies. Additionally, the centre of the identified host lies directly along the line joining
the two emission peaks implying that this is indeed the host. However, there does appear
to be a small, roughly circular, area of emission bordering the galaxy to the south east. It
is unclear what this emission is as it is only slightly more prominent than the remainder
of the jetted emission, it could be due to a knot or some other feature within the jet itself.
However, it is also possible that this host has been misidentified and that the emission
emanates from the core of an unseen host.
To see if the host has been misidentified, I re-examined the SDSS survey (Abolfathi et al., 2018); however, no other potential hosts could be found. In particular, there are no sources located at the position of this potential core. The SDSS survey is 95 per cent complete at a limiting magnitude of 21.6, 22.2, 22.2, 21.3 and 20.7 in the u, g, r, i and z-bands respectively so that if this were the core of an unseen host it would have to be fainter than these magnitudes. Similarly, the Pan-STARRS survey (Chambers et al., 2016) also has no detections within the area of the potential core. The Pan-STARRS survey goes even deeper than SDSS reaching a limiting magnitude of $\sim 24$. This effectively rules out the possibility of the radio emission being due to a galaxy within the local universe, although it may still be due to a quasar or galaxy that is located beyond the sensitivity of our instruments.

The possibility of an unseen, high-redshift host must therefore be considered. The SDSS Quasar survey spectroscopically analyses all quasars with an i-band absolute magnitude less than $-20.5$ (Pâris et al., 2018). Ignoring the effects of dust extinction and assuming a flat spectrum a quasar at this magnitude would be visible within SDSS if it had a redshift of $\sim 0.4$ or less and visible in Pan-STARRS if it were at a redshift of $\sim 1.1$ or less.

Were the observed radio emission located at the SDSS limiting redshift it would have a total linear extent of approximately 450 kpc and a luminosity at 150 MHz of about $10^{26}$ W Hz$^{-1}$. At the Pan-STARRS limiting redshift it would have an absolute size of over 650 kpc and a 150 MHz luminosity of about $10^{27}$ W Hz$^{-1}$. High redshift radio galaxies do
4.3. Sources in the VS but not the AS

Figure 4.5: Images of all the VS sources. Images show LOFAR contours in gold overlaid on an i-band SDSS image in colour. The red cross indicates the location of the LoTSS DR1 host. The LOFAR beam is shown in the bottom left and a scale bar in the bottom right. Radio contours are shown at $3 \times 2^n$ times the local RMS where $n \in \{0, 0.5, 1.0, \ldots\}$. 
Figure 4.5: (continued)
4.3. Sources in the VS but not the AS

Figure 4.5: (continued)
have very high luminosities typically ranging from $L_{150} = 10^{26}$ to $10^{30}$ W Hz$^{-1}$ (De Breuck et al., 2010; Saxena et al., 2019) and so it is possible that there is an unseen host beyond these redshifts.

However, whilst radio sources of this size and luminosity are not unheard of, less than 0.01 per cent of LoTSS sources (389 in total) exceed both SDSS criteria and less than 0.001 per cent (74 in total) exceed the Pan-STARRS criteria. Whilst the number of sources with measured redshifts (and hence measured luminosities) within the LoTSS DR1 survey starts decreasing at about $z \sim 0.8$, Mingo et al. (2019) has used data from the forthcoming LOFAR Deep Field Survey to show that the distribution of radio source sizes is broadly similar at redshifts up to about 1.5.

Therefore, an unseen optical host located at the edge of our detection range, generating radio jets of the required size and luminosity would, whilst not unheard of, be rare. At higher redshifts the size and luminosity of the radio emission would have to be even larger making such a source increasingly unlikely. Whilst further observations are required to definitively identify the host galaxy, the location of the host on the line joining the two
4.3. Sources in the VS but not the AS

emission peaks plus the fact that the potential ‘core’ could easily be due to some anomaly within the jet mean I believe the host has been correctly identified and have kept this source in the VS.

4.3.2 ILT J121847.41+520128.4

One of the most striking features of ILTJ121847 is the extreme angle of the lobes which are inclined at an angle of approximately 20° compared to the major axis of the galaxy (Figure 4.8). Whilst jets can exist at any angle with respect to the host, the majority tend to have differences between 40° and 60° (Gallimore et al., 2006). Even if it does not preclude the jet-related nature of the emission, the angle of 20° certainly makes this an unusual object.

The WISE colour-colour plot for all the selected sources can be seen in Figure 4.9, with ILTJ121847 highlighted with a black circle. The lines shown on the plot are those used by Mingo et al. (2016) to identify AGN ($W_1 - W_2 \geq 0.5$), Ultraluminous Infrared Galaxies (ULIRGs) ($W_2 - W_3 \geq 3.4$) plus the ‘typical’ demarcation line between spiral and elliptical hosts ($W_2 - W_3 = 1.6$).

Using this classification, the location of this source in the bottom right of the plot indicates this galaxy may be a ULIRG. Since the dusty nature of ULIRGs means they are sites of intense star formation the possibility of star driven winds must be considered, although the existence of star formation does not preclude there being a jet as well (e.g. Perna et al., 2021). In particular since the $W_1 - W_2$ colour is 0.332 (i.e. less than 0.5)
Figure 4.7: Image of ILTJ112543 showing the LOFAR emission in gold and the FIRST emission in white overlaid on the SDSS i-band optical image. The red cross shows the position of the optical ID. The LOFAR beam is shown in the bottom left and a scale bar in the bottom right.

Radio contours are shown at $3 \times 2''$ times the local RMS where $n \in \{0, 0.5, 1.0, \ldots\}$.
Figure 4.8: Image of ILTJ121847 showing the LOFAR emission in gold and the FIRST emission in white overlaid on the SDSS i-band optical image. The red cross shows the position of the optical ID. The LOFAR beam is shown in the bottom left and a scale bar in the bottom right. 

Radio contours are shown at $3 \times 2^n$ times the local RMS where $n \in \{0, 0.5, 1.0, \ldots\}$. 

4.3. Sources in the VS but not the AS
this suggests that the emission from the host is star formation dominated although these classifications are less reliable at lower luminosities (Herpich et al., 2016; Mateos et al., 2012). It has been shown that due to pressure gradients within the ISM stellar winds are typically aligned with the minor axis (Kharb et al., 2016), which the radio emission in this source is certainly not. This, the FRII-like morphology of the source and the fact that most ULIRGs also display AGN activity (Somerville & Davé, 2015), means the observed emission is certainly jet related.

The dusty nature of ULIRGs is often explained as being the result of mergers and is expected to provide sufficient fuel to start AGN activity (Wright et al., 2010). Therefore, the possibility of merger-induced AGN activity should also be considered. In particular since it is commonly assumed that the orientation of the jet is determined by the black hole’s spin (e.g. Tchekhovskoy et al., 2011; Gardner & Done, 2018), a binary merger where the spin axis of two supermassive black holes were misaligned could explain extreme jet angles. For example, in this case one black hole oriented at approximately 20° to the major axis of the other galaxy could explain the observed jet angle. This possibility is not precluded by the fact that the host does not show any obvious morphological signs of having undergone a recent merger since AGN activity can be triggered at any time during the merging process. In particular it is anticipated that many low-luminosity AGN will be triggered only after the merger process is complete (Tadhunter, 2016a). Whilst ULIRGs
4.3. Sources in the VS but not the AS

are generally associated with major mergers this need not always be the case (Somerville & Davé, 2015) plus the diffuse nature of the tell-tale signs of past mergers can often have very low surface brightness' (Tadhunter, 2016a) making them difficult to observe, especially in the case of a minor merger where significant disturbance would not be expected (Lotz et al., 2010).

It is also possible that the jets are in fact produced by a second galaxy that is obscured from view. Whilst both the FIRST and LOFAR emission do appear very slightly offset from the galaxy centre they are still located within the region where an AGN would be located. Although unused as part of their criteria, H19 did identify a luminosity above which hosts can be considered to have a radio-excess resulting from the presence of a radio-loud AGN. This is the black line shown in Figure 4.10. Whilst H19 state that this line is unreliable for quiescent galaxies where the star formation rates may be underestimated, the host of ILTJ121847 is certainly not quiescent and its locus on this plot (shown by the black circle) indicates the observed host could contain the associated AGN, although the fact that the host is a spiral may mean that tests such as this, which have been calibrated using predominantly elliptical hosted galaxies, may be unreliable.

The core has a spectral index of 0.6, which is fairly typical of an AGN (Heesen et al., 2014) and although not atypical of star formation (Condon & Ransom, 2016), when combined with the fact that this galaxy also has a radio excess (Figure 4.10) this strongly suggests we are observing the host. The location of the core and lack of any obvious signs of a major merger mean this would have to be occurring directly along our line of sight making this arrangement highly unlikely.

However, despite having properties consistent with being a high excitation source (see Section 4.8 of the main text), plotting this source on a BPT diagram (see Figure 4.11) and using the Kauffmann et al. (2003b) dividing line suggests that this host does not contain an AGN. The criteria of Kauffmann et al. can misclassify sources with low emission line strengths (Stasinska et al., 2006) plus, as above, the spiral nature of the host may mean that this method is unreliable. Therefore, whilst the radio properties suggest the host has been correctly identified, the optical properties do not. It remains possible that the host has been misidentified and that the true host is obscured from view.

In summary, whilst the possibility of a misidentified host cannot be ruled out, this system is consistent with being a ULIRG galaxy that is also producing genuine galaxy-scale jets. The fact that this galaxy is a ULIRG does not affect either the optical or X-ray measurements obtained for the galaxy. The angle of the jets also means that the measurements of the jet/lobe radio flux density is largely free from any contamination caused by the star-forming regions. I therefore retained this object within the VS.

4.3.3 ILT J123158.50+462509.9

ILT J123158.50+462509.9 is a spectroscopic source with a redshift of \( z = 0.11 \). Morphologically it strongly resembles a jetted source with extended radio emission to both the east and west of the source (see Figure 4.12). Both structures have similar lengths and
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Figure 4.10: Plot of $L_{150}$ against the median star formation rate taken from the MPAJHU database. The black line shows the division proposed by H19 for radio-loud / star-forming galaxies with radio-loud galaxies being located above and to the left of the line. ILTJ121847 is circled in black.

Figure 4.11: BPT plot for the AS and VS. ILTJ121847 is shown circled in black. The dividing line of Kauffmann et al. (2003b) separating objects classed as star-forming and AGN is shown in black where AGN are located above and to the right of the line.
luminosities suggesting we are looking at the source close to face on. Whilst there is a faint background galaxy that could explain some of the western emission, this is unlikely to be responsible for the rest of the observed emission and no other background sources are detected in either SDSS or PanSTARRS.

The optically identified host lies in the middle of the radio emission and exhibits a small amount of additional radio flux that could be due to either star formation or a radio core, though the central emission is slightly off-centre making the star formation explanation slightly more likely though neither possibility can be ruled out. Overall, I am confident the host has been correctly identified.

As a spectroscopic source, ILT J123158.50+462509.9 was analysed by Sabater et al. (2019) based on its position in two radio-loudness plots, the BPT diagram and the WISE colour-colour plot. However, all four of their tests suggested this was not an AGN leading H19 to classify this as a star-forming galaxy. This is an anomalous source having one of the lowest radio luminosities in my sample ($L_{150} \sim 4 \times 10^{22}$ W Hz$^{-1}$) but also one of the highest star formation rates ($\sim 10^{0.6}$ $M_\odot$ yr$^{-1}$ according to the MPA-JHU database) and is a borderline ULIRG on the WISE colour-colour plot. Since radio luminosity is expected to increase with higher star formation rates, this may explain why it failed the radio-loudness tests of H19.
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The catalogue of H19 aims to be clean rather than complete so that some genuine AGN are excluded from their sample. As the only elliptically hosted source in the VS that is not also in the AS this source does therefore suggest that there may be a small sub-sample of GSJ that cannot be detected using traditional methods alone.

4.4 Results

In this section I compare the properties of my GSJ sample to those of larger radio galaxies, in order to discover how they fit into the overall picture of galaxy life cycles and the potential effects of feedback on the host. In Section 4.4.1 I discuss the redshift, morphology and luminosity distributions of the GSJ radio emission. In Section 4.4.2 I investigate the host properties of the sample to see what type of galaxies host GSJ. In order to compare the radio properties of the GSJ with a parent sample of larger radio galaxies, I use the 3,820 resolved objects with a redshift less than 0.5 from the catalogue of H19, referred to as H19Resolved.

4.4.1 Redshift and Radio Properties

The distributions of redshift and luminosity for the GSJ sample is shown in Figures 4.13 and 4.14 respectively. As discussed in Section 4.5, as redshift increases it is increasingly difficult to identify GSJ. Hence, it is to be expected that the distribution of my sample is biased towards lower redshifts, with a marked decrease in the numbers of objects with redshifts greater than 0.3. The luminosities of the TS are tightly distributed about a mean value of $\log(L_{150}) = 23.7$ W Hz$^{-1}$, with a standard deviation of 0.6. The AS and VS have similar distributions. These values are offset from the H19Resolved sample whose mean luminosity is $\log(L_{150}) = 24.5$ W Hz$^{-1}$ and exhibits a wider spread of values, with a standard deviation of 1.1. My population of GSJ therefore forms a distinct subset within the H19Resolved sample, as expected given my selection criteria.

It is also informative to compare the GSJ with the catalogue of Jimenez-Gallardo et al. (2019), hereafter JG19, which contains 43 FRII objects of similar physical size to my GSJ, but with 150 MHz luminosities in the range $\sim 10^{24}$ to $10^{26}$ W Hz$^{-1}$. The difference in luminosity is to be expected, as the JG19 sample was drawn from the shallower, but much wider, FIRST survey, and so represents relatively rare, higher luminosity objects. Using the higher sensitivity of LOFAR I am able to reveal for the first time the larger population of small, low-luminosity sources.

4.4.1.1 Radio Morphology

I used the LoMorph code of Mingo et al. (2019) to provide a systematic classification of my sources as either FRI or FRII, using the traditional definition of whether the peak flux density is closer to the centre or to the edge of the source respectively. I find 67 FRI-type sources (65 and 16 within the AS and VS respectively) and 8 FRII-like sources (8 and 1 respectively). The remaining objects are either too small and faint to be classified
4.4. Results

![Redshift distributions](image1)

**Figure 4.13:** Redshift distributions for the AS, VS and TS. The dotted black line in each diagram shows the normalised distribution for the H19Resolved parent sample.

![Luminosity distributions](image2)

**Figure 4.14:** Luminosity distributions for the AS, VS and TS. The dotted black line in each diagram shows the normalised distribution for the H19Resolved parent sample.
automatically by LoMorph or have a mixed morphology (notably this includes ILTJ112543, discussed in Section 4.3, which I visually classified as an FRII). Unfortunately, as Mingo et al. note, LoMorph is less reliable when applied to small, FRI-like objects. As a result, I visually checked these sources, finding that a small number of GSJ have been misclassified (for example I classified ILTJ121847 as an FRII whilst LoMorph classifies it as an FRI), though overall the results are qualitatively the same, with the majority of FRI sources being correctly classified.

Though they acknowledge multiple exceptions, Best (2009) found that for luminosities above $10^{25}$ W Hz$^{-1}$ (at 1.4 GHz), equivalent to $\sim 10^{26}$ W Hz$^{-1}$ at 150 MHz, the majority of sources are classed as FRII. However, all of the FRII-like sources in my sample have luminosities below this limit, which is consistent with the recent samples of lower-luminosity FRIIs found by Mingo et al. (2019) and Capetti et al. (2017).

4.4.1.2 Spectral Indices

In this section I consider the integrated spectral indices for my sample and compare them with the wider populations of compact and extended radio galaxies. Relationships between integrated spectral properties, redshift and size are expected on theoretical grounds, and have also been seen in large samples (e.g. de Gasperin et al., 2018; Tisanić et al., 2020), although the effect of flux density limits must be accounted for (e.g. Sabater et al., 2019). Core-dominated and compact sources typically have flat integrated spectra at low frequencies, due to the effects of synchrotron self-absorption and free-free absorption (e.g. O’Dea & Saikia, 2021). For extended, optically thin sources, regions of flatter spectral index are associated with locations of recent particle acceleration (e.g. Heavens et al., 1987) as are found at the base of FRI jets (e.g. Laing & Bridle, 2013), whereas steep spectrum emission is typically associated with older plasma (although in some cases a comparatively steep injection spectrum is possible).

As already noted in Section 4.2.1, my sources are all resolved at 150 MHz and, applying the criteria of Kellermann & Pauliny-Toth (1981), they are all over 4 orders of magnitude too large to be optically thick so that any self-absorbed component will be insignificant. Whilst my sources are also far larger than the intervening structures typically assumed to cause free-free absorption (O’Dea & Saikia, 2021), simulations show that at low frequencies free-free absorption does become more prominent, especially in the core regions (Bicknell et al., 2018). Therefore, whilst the main cause of any change in the spectral slope of my sources is plasma age, some contribution from free-free absorption is possible.

To calculate the spectral index for each GSJ I used the 1.4 GHz flux densities from the NVSS (Condon et al., 1998) and FIRST (Becker et al., 1995; White et al., 1997) surveys. I cross-matched my sample of GSJ using a 20 arcsec search radius against NVSS and 5 arcsec search radius against the FIRST catalogue, before visually inspecting the matches to ensure they were referencing the same source. Multi-component objects, such as FRII-like sources, can have multiple catalogue entries and so I also manually checked the higher
angular resolution FIRST catalogue against all of the GSJ and if multiple components were found I used the cumulative flux density.

FIRST has a limiting sensitivity of 1 mJy, and so is more sensitive than NVSS at 2.5 mJy. However, the largest angular size to which NVSS is sensitive is greater than that of FIRST. As a result, for those GSJ with a measured size of less than 30 arcsec across I used the FIRST values to calculate the spectral index. At my 30 arcsec limit, estimates show FIRST recovers 77 per cent of the flux density, though this rapidly increases for smaller sources (see Becker et al., 1995, for details). For larger objects I used the measured NVSS flux densities. I then used the methods described in Section 3.3.8 to calculate the integrated spectral indices, calculating limits for those objects that are undetected in either NVSS or FIRST.

For the 75 objects with 1.4 GHz detections, I found an average spectral index of \(0.60 \pm 0.12\). However, excluding those sources with flux densities below 20 mJy, where the selection effects in the LoTSS sample are most prevalent (see Sabater et al., 2019, for details), the average becomes \(0.70 \pm 0.12\) (see top panel of Figure 4.15). This is consistent with the values seen in more powerful radio-galaxy populations (e.g., the 3CRR sample of Laing et al. 1983, with a typical spectral index of \(\alpha = 0.76\), as well as the value of \(0.6 \pm 0.1\) found by Heesen et al. (2014) when studying a different GSJ, NGC 3801, and the value of 0.63 found by Sabater et al. (2019) when analysing the wider LoTSS AGN sample. My spectral indices are consistent with the range of values found by JG19, though my average is slightly steeper than the peak value they found of 0.5, possibly due to the hotspots in their small, luminous FRII sources being more dominant.

Resolved sources larger than a few hundred parsecs typically have spectral indices steeper than 0.5. Therefore, using FIRST images, I visually examined the 23 sources with a spectral index flatter than 0.5. I found that they are all unresolved at the 1.4 GHz frequency of FIRST, so that for this subset the spectral index is dominated by the core properties and does not provide any information about source age or particle acceleration history. For the remaining sources, the integrated spectral index is providing a crude measure of age for the extended GSJ sources, with the comparatively steep spectrum sources likely to be older than those with flatter spectra, although I cannot rule out a contribution from free-free absorption for the smallest sources.

For the sources above 20 mJy, I found that those sources with steep spectral indices are more likely to have a large physical size within the sample range, with only one source having \(\alpha > 0.9\) and a physical size less than 60 kpc. I test if the size-spectral index relation is caused by a relationship between flux density and size (bottom panel of Figure 4.15). However, I find no relationship between the flux density and size showing that the spectral index-size relation present in my sample has a physical origin (e.g., Ker et al., 2012).

As a final comparison, I compare with the population of CSS sources - these are powerful, physically small sources with a turnover in the spectral frequency below about 500 MHz, above which they have a steep spectral index. Whilst 5 of my sources are smaller than the 20 kpc limit typically used to identify CSS, none of them are sufficiently powerful
Figure 4.15: The top panel shows spectral index vs total radio length and the bottom panel shows 150 MHz total flux density vs total radio length. Only sources with a total flux density greater than 20 mJy are shown. Though typically very small, errors in the total radio length have been omitted for clarity. For the faint source I could only derive an upper limit for the spectral index. Errors on the total flux density are too small to be seen.
(see O’Dea & Saikia, 2021, and references therein), making the two categories distinct. This is likely due to a combination of the 12 arcsec cut and lower jet:galaxy ratio used during my sample selection (Section 4.2.2) and so some overlap is anticipated once smaller GSJ are discovered in future, higher angular resolution surveys.

4.4.2 Host Galaxies

I wish to compare the host properties of my GSJ with a larger sample of radio-galaxy hosts. When comparing photometric properties, I use the same sample as Section 4.4.1, while for spectroscopic properties I use only the 170 GSJ with spectroscopic measurements, comparing these with the 2,544 such objects in the H19 sample, hereafter H19Spec. The comparisons discussed in this section are summarised in Table 4.2 and Figure 4.17.

4.4.2.1 Host Morphology

To examine the host-galaxy morphologies for my sample I used the results of the Galaxy Zoo project (Lintott et al., 2008). I found that 13 of my GSJ were hosted by spirals: 12 are in the AS only and one, ILTJ121847, is in the VS only. As expected, the majority of hosts with a definite classification are ellipticals (see Figure 4.16). Applying my own visual classification to the indeterminate sources from Galaxy Zoo, I found an additional three spiral-hosted sources that appear in the AS only and one, ILTJ112543, that is in the VS only, resulting in 15 AS and 2 VS spiral-hosted sources.

Based on my visual inspection of the 15 AS spiral-hosted sources, eight appear to be star-forming galaxies of which three have strong radio cores. The radio emission from four of the spirals is Gaussian in shape whilst one has a continuous region of radio emission that appears to overlap with emission from background galaxies. Two sources have strong Gaussian radio emission on one side of the host only that may be from a background source, though no host galaxy can be seen. To test if these are contaminants, I adopted the emission-line criteria of Kewley et al. (2006), finding that none of these spiral-hosted sources are classified as strongly star-forming. In particular, the three sources with strong radio cores are classified as LINERs with an additional three being classified as Seyfert galaxies. Whilst this is not surprising as part of the test adopted by Kewley et al. (the [NII]/Hα vs [OIII]/Hβ BPT test) was also used by H19 when identifying radio-loud sources, the additional tests used by Kewley et al. show that even if there is some star formation related emission present, these sources do have low levels of AGN activity and can be considered as GSJ.

The two spiral-hosted sources in the VS both exhibit strong FRII-like radio morphologies and have been discussed in detail in Section 4.3. These unusual objects belong to the class of so called spiral DRAGNs (Kaviraj et al., 2015b), with the luminosity of these two GSJ being similar to the low-luminosity spiral DRAGN of Mulcahy et al. (2016).

Overall spirals comprise 4 per cent of the VS and 9 per cent of the TS. Whilst the results from the VS are consistent with those surveys conducted at higher frequencies which show that spiral hosts comprise less than 5 per cent of the total radio-loud population.
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(Tadhunter, 2016a), the fraction in the TS is marginally higher. Active nuclei in spirals are generally less powerful and so this increased percentage may be due to the majority of my sample being lower luminosity than that of Tadhunter. However, it may also be that spiral-hosted AGN are more easily detectable at low frequencies or that they are more likely to host GSJ.

I also looked for merger signatures, using the r-band images from the Pan-STARRS survey, but only found one source (ILT J150245.73+533042.7) that shows any obvious signs of having undergone a recent merger. However, for many sources the optical image quality means it is impossible to rule this possibility out.

Finally, I also compared the concentration indices, C (where $C = R_{90}/R_{50}$), for my GSJ sample with the H19Resolved sample. As shown in Table 4.2, the concentration values are consistent to within their errors, and consistent with expectations for elliptical/bulge-dominated galaxies which have concentration indices above 2.6 (Heckman & Best, 2014). The two spirals in the VS both have concentration indices about 2.2, typical of disc-dominated systems, but the 15 AS spirals have concentration indices ranging from 2.2 to 3.2 with a mean value of $2.6 \pm 0.3$. Therefore, whilst the spirals do have generally lower concentration indices than the elliptical hosts, they are bordering on being considered bulge dominated. This is also different to the results of JG19 who found no sources with concentration indices less than 2.86. This is likely to be due to the higher sensitivity of LOFAR detecting lower levels of emission from spiral/less bulge-dominated sources.
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4.4.2.2 Colour and Magnitude

I also considered the colour and brightness of the host galaxies. The $u - r$ colour and absolute i-band magnitude, accounting for Galactic dust extinction and K correction (Chilingarian et al., 2010; Chilingarian & Zolotukhin, 2012), are shown in Figure 4.17, along with the normalised distribution for the H19Resolved sample.

Following Kaviraj et al. (2015b) who studied the colours of a selection of spiral-hosted AGN I define a ‘blue’ galaxy as having a $(u - r)$ colour less than 2.2. Using the Agresti-Coull method (Agresti & Coull, 1998) to estimate the uncertainties I found that, as expected, my spiral hosts are generally bluer than the elliptical hosts with both VS spirals and $8^{+5}_{-4}$ per cent of the VS ellipticals classed as blue. The AS has $20^{+12}_{-8}$ per cent of the spirals and $12 \pm 3$ per cent of the ellipticals classed as blue. Overall, my GSJ have an average colour of about $2.7 \pm 0.7$, consistent with the average of $2.6 \pm 1.1$ for the H19Resolved sample.

The absolute i-band magnitudes of my GSJ are typically between $-24$ and $-21$ with an average value of $-23.1 \pm 0.8$, identical to the H19Resolved sample and consistent with the JG19 sample. Whilst my spirals are typically fainter with an average value of $-22.1 \pm 1.5$, they still fall within the same range of magnitudes as the elliptical hosts. The notable exception to this is the VS spiral, ILTJ112543 whose host is particularly faint with an absolute magnitude of approximately $-17.0$. The other VS spiral-hosted source also has an absolute magnitude of about $-20.4$, towards the lower end of my range. Both of these objects were discussed in Section 4.3.

4.4.2.3 Stellar and Black Hole Masses

Using SDSS stellar mass estimates, which were derived using the methods of Kauffmann et al. (2003a), the TS has a mean stellar mass of $\sim 10^{11.2^{+0.4}_{-0.4}} M_\odot$, very close to the value of $\sim 10^{11.3^{+0.3}_{-0.3}} M_\odot$ found for the H19Spec sample. This is slightly lower than the characteristic value of $10^{11.5} M_\odot$ identified by Heckman & Best (2014) at which the overall population of AGN switches from releasing energy primarily through radiation to jets, but is consistent with the range ($\sim 10^{11}$ to $10^{12} M_\odot$) identified by Heckman and Best as being typical of radio-loud galaxies. The spiral-hosted sources do have a slightly lower average stellar mass of $\sim 10^{10.7^{+0.8}_{-0.8}} M_\odot$, but consistent within the large uncertainty for this smaller sub-sample. Figure 4.17 shows one significant outlier with an unusually low stellar mass of $\sim 10^{8.6} M_\odot$, allowing it to be classed as a dwarf galaxy (Yang et al., 2020). This is the spiral-hosted source ILTJ112543. ILTJ121847, the other spiral-hosted VS source, is the next least massive source in my sample with a stellar mass of $\sim 10^{9.8} M_\odot$.

Black hole masses were estimated using the $M-\sigma$ relation of McConnell & Ma (2013). I excluded four objects from the spectroscopic sample due to having measured velocity dispersions below the spectral resolution limit of SDSS. The average estimated black hole mass for both the AS and VS are $10^{8.6^{+0.5}_{-0.5}}$ and $10^{8.8^{+0.4}_{-0.4}} M_\odot$ respectively, with the H19Spec sample having an average of $10^{8.7^{+0.6}_{-0.6}} M_\odot$. My values are consistent with the average of $10^{8.5} M_\odot$ found by JG19 and places these objects within the range of black hole masses.
identified by Heckman & Best (2014) of $10^8$ to $10^{9.5} \, M_\odot$ as typical of radio-loud AGN. As expected, the AS spirals have lower black hole masses with an average of $10^{7.7\pm0.4} \, M_\odot$, placing them on the boundary of what is typical of a radio-loud AGN.

### 4.4.2.4 Stellar Properties

Spectroscopic sources within the SDSS database have estimates of the SFR derived using the methods of Brinchmann et al. (2004). Although optical AGN activity can cause SFR estimates to be too high, this is unlikely to be significant for my GSJ sample, as most FRI-type radio galaxies, such as the majority of my sample, have very little nuclear line emission, making them optically similar to ordinary non-active galaxies. Further, Brinchmann et al., adapt their methods to account for those sources identified as hosting an AGN. The average SFR of the spectroscopic GSJ for the TS is $10^{-0.8\pm0.6} \, M_\odot \, yr^{-1}$, consistent with the $10^{-0.6\pm0.6} \, M_\odot \, yr^{-1}$ of the H19Spec sample, and with the SFR of less than $10^{0.5} \, M_\odot \, yr^{-1}$ expected for radio-loud AGN not undergoing a starburst (Tadhunter, 2016a).

I found no difference between SFRs for the AS and VS but, as expected, the AS spiral galaxies have higher star formation rates than the elliptical hosts ($10^{0.2\pm1.0} \, M_\odot \, yr^{-1}$), albeit with large uncertainty. The major exception to this is the VS source ILTJ112543 which I classified as a spiral (though not identified as such by Galaxy Zoo) and which has a particularly low SFR just above $10^{-3.0} \, M_\odot \, yr^{-1}$.

Kauffmann & Heckman (2009) found that active star-forming galaxies have a 4000 Å break strength less than 1.4 whilst passive galaxies have a break above 1.7. The average 4000 Å break strength for the AS, VS and TS is around $1.9 \pm 0.2$ and is therefore fairly typical for an evolved population of hosts. As expected, the AS spirals within my sample have a lower break strength of about $1.5\pm0.4$, but again consistent within the uncertainties. Both VS spirals have lower 4000 Å break values of 1.1. This is different to the results of JG19 who only found one source with a 4000 Å measurement less than 1.7. Again, this difference with JG19 is likely to be due to differences between low and high luminosity host galaxies.

Finally, the stellar surface mass density for my sample is shown in Table 4.2 and Figure 4.17. Again, I found results in line with typical properties of elliptical galaxies (e.g. Heckman & Best, 2014). Consistent with their spiral nature, the two VS spirals both have smaller surface mass densities of $10^{7.5\pm0.0}$ and $10^{7.9\pm0.0}$ for ILTJ112543 and ILTJ121847 respectively.

### 4.4.2.5 Summary

Figure 4.17 and Table 4.2 demonstrate that the colour, absolute magnitude, stellar mass, black hole mass, SFR, 4000 Å break, concentration index and surface mass density for my GSJ samples all have similar mean values and distributions when compared to the H19Resolved/H19Spec parent sample. GSJ are therefore hosted by galaxies that are typical of the broader radio-galaxy population. The number of spiral hosted GSJ is sufficiently small that this result is true even if these sources are excluded.
4.5. Selection Effects

Even though the number of spirals within my sample is relatively small they do form a distinct subset within the population. The AS spirals have properties more typical of the wider population of spiral galaxies with higher host magnitudes, relatively blue colours, lower stellar and black hole masses, lower 4000 Å break strengths, lower surface mass densities, higher star formation rates and lower concentration indices. However, overall the difference in these values is marginal compared to the H19Resolved/H19Spec sample, with the spirals typically having larger errors. This may suggest that the central jet-generating regions of spiral-hosted GSJ are also similar to those of larger elliptically-hosted radio-loud AGN. In contrast, the two VS spirals are notable exceptions with significantly different host properties, making them particularly interesting objects for follow-up observations.

4.4.3 Environmental Richness

To investigate the large-scale environments of the GSJ, I used the catalogue of Croston et al. (2019) which crossmatches LoTSS AGN with the SDSS cluster catalogues of Wen et al. (2012) and Rykoff et al. (2014) to estimate cluster richness. Adopting a matching probability greater than 80 per cent, 17 of my GSJ have a match in the catalogue of Rykoff et al. and 38 have a match in the catalogue of Wen et al., with 13 having a match in both. I therefore report my results using matches from the Wen catalogue, though the results are qualitatively the same when using either catalogue.

Those GSJ with a match are shown in Figure 4.18, where I use the $R_{L_\star}$ richness indicator of Wen et al., which, they define as the approximate number of cluster galaxies within the $r_{200}$ radius. Those sources with a match are broadly consistent with the average relationship found by Croston et al. between cluster size and radio luminosity. The majority of GSJ with a cluster match are located near the catalogued cluster centre, however, those GSJ in larger groups tend to be found away from the cluster centre. Along with the lack of any secondary galaxies in the majority of the cut-out images (see Figure 4.5) this indicates that the matched GSJ are observed predominantly in relatively poor/sparse environments.

The majority of GSJ do not have a match. At a redshift of 0.42, the Wen et al. catalogue is > 95 per cent complete above $M_{200} > 10^{14} M_\odot$ for clusters with a size $R_{L_\star} \geq 12$ whilst at higher redshifts the cluster sizes are likely to be under-reported. Of the 157 unmatched sources, only five have a redshift greater than 0.42 meaning the unmatched sources are also located in poor/sparse environments. GSJ are therefore found in similar environments to the FR0 population, which are typically found in groups of less than 15 galaxies (Capetti et al., 2020).

4.5 Selection Effects

The criteria adopted in Section 4.2 to reduce the number of candidate sources from which both the AS and VS samples are drawn introduced selection effects. In this section I estimate both the number of sources missing from my sample due to these effects and the effect these missing sources will have on the prevalence of GSJ (Section 4.6). In order
<table>
<thead>
<tr>
<th></th>
<th>TS</th>
<th>TS(Spiral)</th>
<th>AS</th>
<th>AS(Spiral)</th>
<th>VS</th>
<th>VS(Spiral)</th>
<th>H19</th>
</tr>
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<td>Host Magnitude</td>
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<td>$-23.1 \pm 0.6$</td>
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<tr>
<td>Star Formation Rate</td>
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<td>1.5 (\pm 0.4)</td>
<td>1.9 (\pm 0.2)</td>
<td>1.5 (\pm 0.4)</td>
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<td>1.1 (\pm 0.0)</td>
<td>1.9 (\pm 0.3)</td>
</tr>
<tr>
<td>BH Mass</td>
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<td>7.7 (\pm 0.4)</td>
<td>8.6 (\pm 0.5)</td>
<td>7.7 (\pm 0.4)</td>
<td>9.2 (\pm 0.5)</td>
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</tr>
<tr>
<td>stellar Mass</td>
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<td>10.7 (\pm 0.8)</td>
<td>11.3 (\pm 0.3)</td>
<td>10.9 (\pm 0.4)</td>
<td>11.2 (\pm 0.5)</td>
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<tr>
<td>Concentration Index</td>
<td>4000Å Break</td>
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<td>8.8 (\pm 0.3)</td>
<td>8.8 (\pm 0.3)</td>
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<tr>
<td>Host Colour</td>
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<td>$1.3 \pm 0.1$</td>
<td>$2.6 \pm 1.1$</td>
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Table 4.2: Comparison of the host properties of the TS, AS and VS with the H19 sample. Also shown is the subset of spiral galaxies from the AS.
4.5. Selection Effects

Figure 4.17: Host galaxy properties for the TS, AS and VS. Black lines show the H19 parent sample, normalised to the TS. Top row: host galaxy colour (left) and absolute (i-band) magnitude (right). Second row: host stellar mass (left) and host SMBH mass (right). Third row: host star formation rate (left) and 4000Å break strength (right). Bottom row: concentration index, $C = R_{90}/R_{50}$ (left) and stellar surface mass density, $\mu_* = 2\pi R_\text{e}^2$ (right).
to do this, I also estimate the luminosity, redshift, stellar and black hole masses of these unobserved sources.

The requirement of a minimum angular size of 12 arcsec means that the smallest sources are only selected at the lowest redshifts. This can be seen clearly in Figure 4.19. Simultaneously I also rejected sources with a proper physical size greater than 80 kpc. At a redshift of just under 0.6, 12 arcsec is equivalent to 80 kpc making it impossible for us to observe any sources above this redshift. In practice, the maximum redshift amongst my sample of sources is 0.4822.

Within the region where GSJ are observed, there is no correlation between jet length and redshift, with the distribution of lengths spread evenly across any given redshift range. Using the (approximate) observed upper redshift of 0.5 as the upper limit, the area of the plot above the 12 arcsec line, where GSJ are capable of being observed represents \( \sim 45 \) per cent of the parameter space. Assuming GSJ are distributed uniformly across this space, I therefore estimate that the \( \sim 55 \) per cent of GSJ we are not observing equates to approximately 240 GSJ within the HETDEX field with a redshift of less than 0.5.

In order to include these unobserved GSJ in my analysis of the prevalence of GSJ (Section 4.6), I assume a population of 240 and assign them representative radio lengths, redshifts and luminosities as well as stellar and black hole masses. I estimate their radio lengths and redshifts by assuming they have the same distribution of values as the observed sources. In order to estimate the luminosity of these missing sources I then found a size-luminosity relation for the observed sources. In order to minimise the effects of redshift on this relation I used only those GSJ with a redshift less than 0.1 (though I get similar...
results using the full TS as well as the lower and upper redshift halves within the $z<0.1$ subset). Although there is a large amount of scatter, this gives a relation between total radio length and luminosity of:

$$\log_{10}(L_{150}) = 22.13 + 0.02(\text{Length/kpc})$$  \hspace{1cm} (4.2)

I used this relation to estimate the luminosity of the unobserved sources.

Finally, using the AGN catalogue of H19 as a base, I binned the AGN according to luminosity with each bin covering a range of one dex. I then found the mean and standard deviation for both stellar and black hole masses for each bin. Gathering the ‘missing’ GSJ sources into the same bin sizes and assuming the same overall distribution of masses as the sample of H19, I used the mean and standard deviation to estimate the stellar and black hole masses respectively. Results of this analysis are presented in Section 4.6.

### 4.6 Prevalence of GSJ

It is well established that the likelihood of a galaxy hosting a radio-loud AGN of any given luminosity increases with both the host’s stellar and black hole masses (Best et al., 2005a; Sabater et al., 2019). In order to determine whether the same relationship is true of my GSJ I adopted the techniques of Sabater et al. (2019) and calculated the fraction of the total number of galaxies that are GSJ at the current time. I also investigate whether the
fraction of radio galaxies that have been classified as GSJ is similarly dependent upon the host’s stellar and black hole mass. As described in Section 4.5, selection effects mean that the smallest, least luminous GSJ cannot be observed. I therefore present results for both the unadjusted sample as well as a sample adjusted to account for selection effects.

To compare the GSJ sample with the wider population of galaxies and to allow a direct comparison with the work of Sabater et al. I took all those galaxies from within the SDSS Main Galaxy Sample that are located within the HETDEX footprint. The Main Galaxy Sample has an approximate upper redshift limit of 0.3, which, in order to produce an unbiased comparison I use as the upper limit within this section, resulting in an unadjusted GSJ sample size of 165 and, since 98 of the ‘missing’ sources have redshifts below 0.3, an adjusted sample size of 263. I divided both samples into bins of stellar and black hole mass (derived as described in Section 4.4.2 for the unadjusted sample and as described in Section 4.5 for the adjusted sample). For each bin I calculated the fraction of galaxies that are GSJ where both have a luminosity $\geq 10^{21}\text{ W Hz}^{-1}$. I then repeated the processes, increasing the luminosity limit by one dex each time up to a maximum of $10^{24}\text{ W Hz}^{-1}$.

The results for the unadjusted sample are shown as the solid lines in the top row of Figure 4.20. The faint dashed lines represent the selection-effect, adjusted, sample. The uncertainties shown were calculated using the Agresti-Coull binomial confidence interval (Agresti & Coull, 1998) with the confidence level set at 68 per cent. For clarity, and because their numbers are too small to be statistically useful, those galaxies with stellar masses below $10^{10.6}\text{ M}_\odot$ are excluded from the plots (see Figure 4.17).

When compared against the wider population of galaxies (upper panels), the fraction of GSJ is directly related to both the black hole and stellar mass. This is entirely consistent with the conclusions of Sabater et al. (2019). However, in contrast to their results, the relation with stellar mass appears to flatten above $10^{11.5}\text{ M}_\odot$ for all luminosity ranges. I tested the significance of this flattening for the most inclusive luminosity group ($L_{150} > 10^{21}\text{ W Hz}^{-1}$) by applying a linear fit to the points up to $10^{11.5}\text{ M}_\odot$. In the absence of a change of slope, I would predict the fraction with stellar masses of $10^{11.7}\text{ M}_\odot$ that are also GSJ to be $0.09 \pm 0.03$ for the unadjusted sample. Since the actual data point is $0.02 \pm 0.01$, the flattening is significant at more than two sigma. With the exception of the highest luminosity group ($L_{150} > 10^{24}\text{ W Hz}^{-1}$), which has a smaller number of sources and is therefore less reliable, the other luminosity groups also show a flattening at more than the two sigma level. The adjusted sample shows a qualitatively similar flattening. I consider the origin of this flattening, not seen for the larger sample of Sabater et al. (2019) in Section 4.8.

As well as investigating the prevalence of GSJ in the Main Galaxy Sample, I carried out a similar comparison using a parent sample of radio-loud AGN, allowing an investigation of the fraction of radio-loud AGN classified as GSJ. For consistency I use the parent sample of Sabater et al. rather than that of H19. The sample of Sabater et al. is limited to a redshift of 0.3, allowing a direct comparison with the above results. The results are shown
4.6. Prevalence of GSJ

**Figure 4.20:** Top Row: Fraction of Main Galaxy Sample galaxies that are GSJ with luminosity above the given limits as a function of black hole mass (left) and stellar mass (right). Bottom Row: Fraction of radio-loud galaxies that are GSJ with luminosity above the given limits as a function of black hole mass (left) and stellar mass (right). Solid lines represent the unadjusted sample, faint dashed lines the adjusted sample.
in the bottom two plots of Figure 4.20. I found that the fraction of radio-loud AGN that are GSJ is independent of black hole mass, remaining roughly constant at $\sim 10$ per cent ($\sim 11$ per cent for the adjusted sample) for GSJ with luminosities above $10^{21}$ W Hz$^{-1}$. The unadjusted fraction of GSJ also remains broadly constant with respect to stellar mass for all except the most luminous group ($L_{150} > 10^{21}$ W Hz$^{-1}$), which is less reliable due to the smaller number of objects. Whilst there is a slight drop in the unadjusted sample at a stellar mass of $10^{11.7} M_\odot$, this is only significant at the 1.5 sigma level.

The adjusted sample also shows that a constant fraction of radio-loud AGN can be considered GSJ, with the exception of the most luminous group where the percentage is inversely proportional to stellar mass. There is no significant decrease in the number of anticipated GSJ at the highest stellar mass. Further studies are needed to see if I have overestimated the numbers of lower stellar mass objects and whether the fraction of radio-loud galaxies that are GSJ does decrease at the highest stellar and black hole masses.

### 4.7 Energetics

To get a first-order estimate of the impact GSJ could be having upon their hosts I compared the internal energy within the radio lobes with the energy within the host’s hot ISM. As mentioned in Section 4.2 the ellipse sizes from the LoTSS catalogue typically underrepresent the true size of my sources. Therefore, rather than using these sizes to calculate the radio energy I instead assumed the radio emission comes from a cylindrical region of typical aspect ratio. Using the VS to determine a typical aspect ratio, I found that the source diameter is typically $0.55 \pm 0.12$ times the length. Assuming this ratio applies across the entire sample, I used the source length and estimated diameter to estimate the radio-emitting volume. Using PySYNCH (see Sections 1.3.1 and 3.3.9) I derived the minimum energy density and hence minimum total energy for each source.

For powerful FRII sources it has been demonstrated that energy estimates within a small factor of equipartition give lobe pressures consistent with those required to inflate the lobes and achieve pressure balance with the environment (e.g. Ineson et al., 2017). However, for FRI-like sources the minimum energy estimates are often insufficient to inflate the observed cavities. This discrepancy is commonly attributed to the entrainment of protons. Based on the results of Croston et al. (2008a) and Croston et al. (2018) I increased the minimum energy estimates for the FRI sources by a factor of 10 to better approximate the true energy within the lobes. I found that for the majority of GSJ, the internal energy ranges from approximately $10^{49.5}$ J to $10^{51.5}$ J (see Figure 4.21), indicating that even the least powerful GSJ contain almost a million times more energy than an average supernova of $10^{44}$ J.

However, these minimum energy estimates represent only the internal energy of the lobes. The total energy available must be higher, to account for the work done in displacing the ISM as well as the existence of any shocks. For a relativistic gas undergoing adiabatic expansion, the total energy is $4pV$ (e.g. Birzan et al., 2004; Heckman & Best, 2014),
4.7. Energetics

Although if shocks are present this figure could be higher (e.g. in Croston et al., 2007, the galaxy-scale jet source NGC 3801 was found to have an energy of up to 6pV). Consequently, an amount of energy equal to at least a third of the observed internal energy has already been transferred to the ISM. As discussed in, for example, Hardcastle & Krause (2013), if shocks are present this figure could be significantly higher.

To find the energy within the hot ISM I estimated the total gravitational mass of each host, using the velocity dispersion relations of Bandara et al. (2009) for the elliptical-hosted GSJ (Equation 7 in their paper) and Davis et al. (2019) for the spirals. I used these relations because the GSJ are predominantly in sparse environments (see Section 4.4.3), and both authors used a selection of individual galaxies to find a direct relation between a galaxy’s total mass and velocity dispersion. I also only considered those sources flagged by SDSS as having reliable spectroscopic measurements. The GSJ sample is, on average, slightly larger than three times the effective radius. Therefore, assuming a Navarro, Frenk and White (NFW) profile (Navarro et al., 1996) with a concentration index of 6, I estimated the total gravitational mass within three effective radii of the host which is approximately the scale of influence of the GSJ.

Assuming a fixed gas mass, I used the median value of 0.047 ± 0.009 found by Dai et al. (2010) using a large sample of groups/clusters (richness class 2 in their terminology) to find the gas mass within each of my hosts. I further assume that the gas mass ratio derived by Dai et al. for groups/clusters can be applied to individual galaxies. This assumption is supported by the gas mass fractions found by Dai et al. are consistent with Trinchieri et al. (2012) who, using X-ray data, found a gas mass fraction of 5 per cent for two galaxies with similar masses and environments to the GSJ sample. This is a conservative assumption,
as the impact of stellar and AGN feedback process that may expel gas will be stronger on galaxy compared to group scales, so that gas fractions may be lower (as is the case for the Milky Way, which has an estimated hot gas mass fraction of around 2-3 per cent (Bland-Hawthorn & Gerhard, 2016)), but are unlikely to be substantially higher. The derived ISM energies are therefore unlikely to be systematically underestimated. Using an average particle mass of \(0.62 \, M_H\) (Goulding et al., 2016) to get the total number of particles within the ISM and assuming a gas temperature of 0.7 keV for the spirals (Li et al., 2017) and 0.5 keV for the ellipticals (Goulding et al., 2016) I derived estimates of the total ISM energy within \(3R_e\) of the host.

Figure 4.21 shows the comparison of internal radio and ISM energies. Whilst the majority of my sources are clustered towards the top right of the plot there are a few sources with lower internal and ISM energies located towards the bottom left. These are typically lower-luminosity sources and may represent a wider population of extremely low luminosity GSJ that it is not currently possible to observe (see Section 4.5).

Figure 4.21 also shows that whilst the majority of GSJ have internal radio lobe energies less than the ISM energy within \(3R_e\) of the host, there are a few with similar internal radio lobe and ISM energy. There are also nearly 50 per cent with an internal radio lobe energy that is within an order of magnitude of the ISM energy. This suggests that even ignoring any shocks, GSJ are capable of significantly affecting the evolution of the ISM within their own host galaxy.

Previous studies of a small number of GSJ show that they can transfer large amounts of energy from the lobes directly into the ISM (Croston et al., 2007, 2009; Mingo et al., 2011; Hota et al., 2012). Whilst I do not have any evidence of any direct coupling between the lobes and host ISM for my GSJ, if the lobes are in pressure balance with their environments, then between 1/3 and 2/3 of the internal energy (depending on whether the lobes are dominated by relativistic or thermal material) must already have been transferred to the environment. Whilst I cannot determine the radius at which this occurred, their small physical size means that GSJ must have already had a significant impact on their hosts. Unfortunately, the future impact of GSJ is harder to determine as it is unknown at what radius and over what timescales the lobes will release their current energy.

Previous studies have shown that GSJ can generate shocks (Croston et al., 2007, 2009; Mingo et al., 2011, 2012). This is investigated further in Chapter 5 where high angular resolution VLA data of nine sources shows that GSJ are potentially capable of producing strong shocks. However, for two GSJ, X-ray observations do not reveal the presence of strong shocks (see Chapter 6) and, whilst the possibility of strong shocks cannot be ruled out, weak shocks are considered more likely. For the remaining GSJ it remains unknown if shocks are present, though if they are this would mean the energetic impact of GSJ on their hosts is likely to be significantly higher than estimated in this section.
4.8 Discussion

In this chapter I have described a method for finding GSJ that identified 454 candidates from among the initial 318,520 sources in LoTSS DR1. From this sample I used the AGN/star formation separation criteria of H19 to automatically select 192 GSJ. Separately, I also visually inspected the 454 candidate sources, identifying 52 GSJ. These samples comprise the AS and VS respectively. Combining the unique sources from each gives the TS of 195 GSJ. In this section I discuss the implications of my results.

4.8.1 Comparison with Other Work

The large number of sources found by modern surveys, such as LoTSS, mean that methods such as those outlined in Section 4.2 will be vital if more GSJ are to be found in future and ongoing surveys. All my GSJ are resolved at 150 MHz with radio emission extending beyond the central confines of the host. My sample have two-sided jet lengths between 10 kpc and my 80 kpc upper limit. These sources are therefore physically bigger than the FR0 class of objects (Baldi et al., 2018b) and the jetted radio cores seen in the LeMMINGS survey (Baldi et al., 2018a). Future, higher angular resolution, releases of the LoTSS survey will allow identification of smaller GSJ amongst the population of currently unresolved sources. A larger sample of GSJ will not only allow better comparisons with these other populations of small sources, it will also provide the numbers necessary to investigate any evolution in the properties and types of GSJ hosts with redshift.

Within my sample I find that a significant minority are producing FRII-like structures typically found in more luminous radio galaxies. However, all my FRII sources have luminosities below the limit of \(10^{26}\) W Hz\(^{-1}\) (at 150 MHz) identified by Best (2009) as the point above which FRII sources are typically observed. My sources are therefore consistent with the results of Mingo et al. (2019) and Capetti et al. (2017), both of whom found populations of FRII sources with luminosities below this limit. Mingo et al. found that the hosts of their low-luminosity FRII sample have lower absolute K-band magnitudes and therefore have lower masses than the hosts of both more luminous FRII sources and the FRI sources of equivalent size and radio luminosity. Whilst the stellar masses of my FRII sources are all below the sample average, my sample is too small to confirm the finding of Mingo et al.

In their recent paper Jimenez-Gallardo et al. (2019) found a population of 43 FRII sources no larger than 30 kpc in size making them comparable to my GSJ. All their sources have luminosity below the traditional FRI/FRII divide. Their sample was identified from FIRST images of 3,357 sources taken from the catalogue of Best & Heckman (2012) with redshifts less than 0.15. Their sample is however comprised entirely of FRII sources and whilst they do find more FRIIs this can be attributed to the larger sky area over which they searched, plus the possibility of contaminants within their sample. Their sources are also more luminous than mine and so they provide a complementary view of the luminous end of the GSJ population.
4.8.2 Spiral-hosted GSJ

I found that between 4 per cent of the VS and 9 per cent of the AS have spiral hosts, though it is possible that some of the AS spirals are contaminants. Whilst all the spiral-hosted GSJ have properties fairly typical of spirals in general, being younger and bluer in colour with smaller masses than the elliptical hosts, this is particularly true for the two VS spirals. This is, however, different from the population of spiral-hosted AGN found by Kaviraj et al. (2015b) where \( \sim 90 \) per cent had a red colour akin to elliptical-hosted AGN, albeit at higher radio luminosities than my sample. Kaviraj et al. also found a high incidence of mergers amongst their population which I do not observe in my sample, although image resolution makes it impossible to rule this possibility out.

My findings therefore support the prediction by Mulcahy et al. (2016) of a population of low-luminosity, spiral-hosted radio-loud AGN. The lack of any obvious mergers within my sample also suggests that secular processes may be responsible for triggering low-luminosity AGN activity (as suggested by authors such as Man et al., 2019; Tadhunter, 2016a) and that in order for these objects to attain the higher luminosities seen in the samples of Kaviraj et al. an event, such as a merger, is necessary to increase the flow of fuel to the AGN. To study these unusual objects properly, it is important to identify other spiral-hosted radio galaxies in future wider area surveys. However, my results show that care must be taken when looking for these objects as traditional selection techniques may miss them.

4.8.3 GSJ Prevalence and Relation to the Wider Radio-galaxy Population

There is a well-established link between both stellar and black hole mass and the fraction of galaxies hosting a radio-loud AGN. This trend has recently been confirmed within the LoTSS DR1 sample (Sabater et al., 2019). As discussed in Section 4.6, my GSJ follow the trend for black hole mass at all masses and they follow the trend for stellar masses up to about \( 10^{11.5} \, M_\odot \), above which there is some evidence that the fraction of GSJ starts to flatten contrary to what is seen in the radio-loud AGN population, though further studies are needed to confirm this trend.

Whilst the observed flattening may be caused by a selection effect I have not accounted for, if genuine, it may be related to my findings in Section 4.4.3 that GSJ inhabit relatively poor environments. Using the LoTSS sample Sabater et al. (2019) established that at the frequencies observed by LOFAR the largest galaxies are always active. If these jets are always turned on, then the constant injection of energy could mean that at the observed frequencies and angular resolution of LOFAR the radio emission from the two jets remains larger than the 80 kpc limit used for finding GSJ. As a result, it might be expected that there would be fewer GSJ found in dense environments and at these high stellar masses.

The constant fraction of the radio-loud AGN population that can be classed as GSJ also shows that for all radio-loud AGN exhibiting a duty cycle (i.e. where the radio
emission appears to turn off at the frequencies and sensitivity of LOFAR) then, provided the conditions for generating jets are satisfied, the likelihood of a source being a GSJ is independent of both black hole and stellar mass. This is to be expected since all larger sources must go through the GSJ stage at some point in their evolution.

My spectral index analysis indicates that GSJ have a range of ages. While care is needed in interpreting integrated spectral indices, the fact that steep spectrum GSJ tend to have large sizes is consistent with those sources being dominated by older populations of electrons (e.g. Heesen et al., 2014). However, large sources are also present in the sample with flatter spectral indices, which may suggest their average expansion speed is higher than the steeper spectrum sources of similar size. As will be shown in Section 5.5.1, at least one source never grew beyond the GSJ stage. It is possible that more of the steeper spectrum, plausibly older, sources will also never grow beyond the GSJ stage. However, all larger radio-galaxies must have been GSJ at some point in their history, and so it is likely that a significant proportion of GSJ do evolve to larger sizes. Detailed population modelling, accounting carefully for selection effects, will be needed to draw stronger conclusions about the relative proportion that will not grow beyond the GSJ phase.

4.8.4 Energetic Impact of GSJ

Though I currently have no direct evidence of the location at which GSJ are transferring their energy to the external medium, my estimates of the energy supplied show that many are capable of significantly heating the surrounding ISM. This supply of energy to the surrounding environment is therefore capable of restricting the gas cooling rate and reducing the flow of material accreted by the galaxy. This in turn suggests that GSJ are capable of affecting the SFR of their own host galaxy. Mulchaey & Jeltema (2010) found that low-mass early type galaxies in sparse/isolated environments, similar to those of my GSJ, have less hot gas than comparable sources in clusters. My conclusion that GSJ are capable of significantly heating their environments suggests that GSJ may be responsible for moving the gas out to larger radii, causing a decrease in density or even driving a fraction of the ISM from the host galaxy entirely in line with Mulchaey and Jeltema’s suggestion that AGN feedback may be responsible for removing this hot gas.

The situation for at least some of my GSJ may be similar to NGC 3801 which, whilst more luminous than my sources, has radio emission about 10 kpc in size and can be considered a GSJ (Heesen et al., 2014). Using X-ray data Croston et al. (2007) found that the jets of NGC 3801 were driving shocks into the host ISM. A similar result was found for Centaurus A where the southern radio lobe is driving a shock front into the host galaxy (Croston et al., 2009). Similarly, Markarian 6 is a Seyfert galaxy with 10 kpc lobes, a luminosity slightly greater than that of my GSJ and radio bubbles of the order $10^{49}$ J placing it towards the lower end of the range of energies associated with my GSJ (Mingo et al., 2011; Kharb et al., 2006). The lobes of Markarian 6 are expanding into the host galaxy creating strong shocks capable of affecting star formation. Finally, Circinus is another Seyfert galaxy where the radio lobes are driving shocks into the host with an
energy of about $10^{48}$ J (Mingo et al., 2012). These sources suggest that GSJ may also be capable of producing shocks. As already mentioned, whilst X-ray studies of two GSJ (see Chapter 6) show that they are not generating strong shocks, future X-ray studies are needed to confirm if this is the case across the wider GSJ population.

4.9 Summary and Conclusions

I have presented a method for efficiently identifying GSJ from within the LoTSS DR1 catalogue. My main conclusions are:

- I have found 195 GSJ with total radio emission no larger than 80 kpc in size; this is the largest sample of intermediate-sized radio galaxies constructed to date.

- 9 per cent of the GSJ population are hosted by spiral galaxies, of which two are highly unusual sources generating FRII-like jets.

- GSJ have luminosities between $3 \times 10^{22}$ and $1.5 \times 10^{25}$ W Hz$^{-1}$ at 150 MHz.

- The host properties of my GSJ show that they are ordinary radio galaxies observed at a stage in their life shortly after the radio emission has expanded beyond the central regions of the host.

- Based on my estimates, about half of my GSJ have internal radio lobe energy within an order of magnitude of the ISM energy. Even ignoring any possible shocks, GSJ are energetically capable of affecting the evolution of their host.

- GSJ can occur across a wide range of source ages with many expected to grow into larger sources, making GSJ a key stage in the life cycle of radio galaxies.

The LoTSS DR1 covers about 2 per cent of the final survey area. I therefore expect that future releases will uncover an ever-increasing population of GSJ. In the future this will include spectroscopic data for all LOFAR sources greater than 10 mJy via the WEAVE-LOFAR survey (Smith et al., 2016) which will allow for the confirmation of more GSJ sources. Furthermore, I also expect that future LoTSS sub-arcsecond surveys will allow the detection and study of GSJ at smaller physical sizes where the jets are affecting the inner parts of the host galaxy. This should also allow unambiguous identification of small jets within strongly star-forming galaxies. This increased population and angular resolution will allow for even more robust studies of this important stage in the life cycle of radio-galaxies.
Chapter 5

VLA high-resolution follow-up

The contents of this chapter have been published in Monthly Notices of the Royal Astronomical Society as Webster et al. (2021b).

5.1 Introduction

In Chapter 4, using data from LoTSS DR1 (itself described in Section 3.1.1), I discovered a population of 195 physically small, low-luminosity ($L_{150\,\text{MHz}} \lesssim 10^{25}\,\text{W Hz}^{-1}$) radio galaxies with total linear sizes of 80 kpc or less. Known as Galaxy Scale Jets (GSJ), these sources have an average redshift of $\sim 0.2$ with a maximum of 0.5 and are hosted by both spiral and elliptical galaxies whose properties were shown to be typical of the hosts of larger radio galaxies (see Section 2.3 for a description of typical AGN host properties).

Numerical simulations have shown that low power radio galaxies, like those identified in Chapter 4, have jets that decelerate quickly, entraining material and transferring most of their energy into the surrounding ISM (Mukherjee et al., 2020; Rossi et al., 2020; Massaglia et al., 2016). Simulations show that low-power jets are likely to deposit their energy throughout large regions of the host galaxy (Mukherjee et al., 2018).

Morphologically the GSJ found in Chapter 4 are a mix of FRI and FRII-type sources. Whilst many have integrated spectral indices typical of larger sources, some have relatively flat spectral indices. Although it was not possible to derive ages for individual sources, the range of spectral indices were interpreted as showing that a wide range of ages were present in the sample. Despite being smaller with lower luminosity than the majority of previously studied radio galaxies, GSJ were found to contain enough energy to potentially have a significant effect on the evolution of the host.

The low frequencies used by LOFAR mean that any core radio emission from the AGN is less prominent. Combined with the 6 arcsec angular resolution of LOFAR (Shimwell et al., 2017) this means that some of the optical host galaxies may have been misidentified in the LoTSS DR1 value added catalogue (Williams et al., 2019). The angular resolution of LOFAR also means that, due to the small size of these sources, the source morphology of many GSJ is often ill-defined.

Unlike the population of FR0 (described in Section 1.2.1), the GSJ sample are all resolved, extended sources with radio emission a few tens of kpc in size. The sample is also distinct from the population of compact CSS/GPS sources, though an overlap is expected
once smaller GSJ are discovered. At present, the relationship between these populations is uncertain. Though not universally accepted, the spectral turnover seen in CSS and GPS sources is often interpreted as these sources being the young progenitors of larger radio galaxies (O’Dea & Saikia, 2021). The small physical size of GSJ therefore means that these sources could be located along any evolutionary path between compact sources and larger radio galaxies.

In Section 4.7, since it was not possible to account for the contribution of shocks, only lower limits on the potential energetic impact could be obtained. As described in Section 1.5, powerful sources are frequently seen to be driving shocks that transfer energy to their surroundings (e.g. Fabian et al., 2003; Croston et al., 2007; Forman et al., 2007; Croston et al., 2009; Randall et al., 2015). However, it is currently unknown whether less powerful GSJ expand fast enough to do the same. Related to this, the amount of time a source will spend in the GSJ stage depends upon its growth rate. Slowly expanding sources will spend more time in the GSJ stage, increasing the opportunity for the energy contained in the lobes to be transferred into the host’s immediate environment.

Combining archival data with new, high angular resolution VLA images of a representative sample of GSJ, in this chapter I aim to address some of these outstanding issues by:

- Verifying the LoTSS DR1 optical host IDs and confirming the AGN nature of the radio emission.
- Better constraining the source morphology, including FR class, so as to relate the radio structures of small jets to those of traditional hundred-kpc scale radio galaxies.
- Using spectral information for each of my sources to measure the integrated spectral index and, where possible, constrain the break frequency so as to be able to draw conclusions about age and expansion speeds.

This chapter is structured as follows. Section 5.2 describes the method used to find a representative sample of GSJ. Section 5.3 describes the image processing. Section 5.4 examines the images, looking for confirmation of the previously identified optical hosts. Section 5.5 looks at the integrated spectral indices for the sample. Section 5.6 presents the spectral maps used in the ageing analysis in Section 5.7. The lobe advance speeds are derived in Section 5.8, there is a discussion of my results in Section 5.9 and Section 5.10 summarises my findings.

5.2 Sample Selection

In this chapter I aim to use a representative sub-sample of GSJ for high angular resolution follow-up. To find the sub-sample I adopted the more stringent visual selection process from Section 4.2.4, as it combines both automated and manual selection criteria to identify GSJ whose jets could be directly influencing the evolution of the host. Applying this selection
5.2. Sample Selection

process to 6 arcsec resolution images from a pre-release version of the LoTSS DR1 catalogue (Shimwell et al., 2019), I identified a sub-sample of nine objects (described in Table 5.1) that, in order to be representative of the wider GSJ population:

- Covers the range of observed radio sizes (up to my 80 kpc limit).
- Covers the range of observed radio luminosities (approximately $10^{22}$ to $10^{25}$ W Hz$^{-1}$ at 150 MHz)
- Includes both elliptical and spiral-hosted sources.
- Includes both FRI and FRII-like sources based on their appearance in the LoTSS DR1 images.

In addition, the limitations of the VLA had to be considered and so, assuming the canonical spectral index of 0.7, only sources that would be both visible and resolved by the VLA were included in the sub-sample. The size and surface brightness of the selected sources meant that they should all be visible in the S-band using the VLA’s B and C configurations.

Whilst the nine sources were identified using a pre-release version of the LoTSS DR1 catalogue they are also representative of the 195 GSJ identified in Section 4.2 using the final DR1 catalogue. As shown in Figure 5.1, the nine sources are spread across the range of sizes and luminosities observed in the GSJ sample.

Six of the nine sources appear in the total sample presented in Section 4.2. Subsequent optimisation of the GSJ selection criteria to exclude star-forming galaxies and larger objects meant that the other three sources identified using the pre-release LoTSS DR1 catalogue, ILT J122037.67+473857.6, ILT J124627.85+520222.1 and ILT J125453.46+542923.4 are not included in the Section 4.2 sample. However, all three sources have combined jet lengths less than my 80 kpc limit with the first two sources also appearing in the radio-loud AGN catalogue of Hardcastle et al. (2019). Both sources can therefore be considered as GSJ.

The third source, ILT J125453.46+542923.4, was initially included because its elongated morphology in the LoTSS DR1 images suggested that this was a genuine GSJ. However, subsequent improvements to the LoTSS image processing pipeline, included in the DR2 release (Tasse et al., 2021), no longer showed the elongated radio emission so that I no longer consider this source to be a genuine GSJ. The VLA data (see Figure 5.2) confirmed that this is not a genuine GSJ.

Of the nine sources sent for high angular resolution follow-up, ILT J121847.41+520148.4 and ILT J112543.06+533112.4 are both highly unusual with spiral hosts and FRII-like morphologies. Consequently, both the 9 per cent of spiral-hosted sources (Section 4.4.2.1) and the $\sim$10 per cent of FRII-like sources (Section 4.4.1.1) in the Chapter 4 sample are marginally over-represented. However, in both cases the over-representation is small and it is useful to have multiple examples of these unusual sources, allowing them to be better understood. Hereafter, as in Chapter 4, all sources are referred to using only the first 10 characters of their respective names.
Figure 5.1: The distribution in the size-luminosity plane of the nine sources for which VLA measurements are presented in this paper compared to the GSJ total sample from Chapter 4. Sources that are part of the GSJ total sample identified in Section 4.2 are highlighted in orange, those that are not are highlighted in purple.

Table 5.1: Details of the sources identified for VLA follow-up. Spectroscopic redshifts are taken from the value-added LoTSS DR1 catalogue of Williams et al. (2019). Luminosities and total radio lengths were derived using part of the LoMorph code of Mingo et al. (2019).

<table>
<thead>
<tr>
<th>Source Name</th>
<th>z</th>
<th>Radio Morphology</th>
<th>Host Type</th>
<th>log$<em>{10}(L</em>{150})$</th>
<th>Length / kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILT J112543.06+553112.4$^a$</td>
<td>0.010</td>
<td>FR II</td>
<td>Spiral</td>
<td>22.5</td>
<td>16</td>
</tr>
<tr>
<td>ILT J120326.64+545201.5</td>
<td>0.050</td>
<td>FR I</td>
<td>Elliptical</td>
<td>22.9</td>
<td>31</td>
</tr>
<tr>
<td>ILT J120645.20+484451.1</td>
<td>0.065</td>
<td>FR I</td>
<td>Elliptical</td>
<td>23.5</td>
<td>69</td>
</tr>
<tr>
<td>ILT J121847.41+520148.4$^a$</td>
<td>0.057</td>
<td>FR II</td>
<td>Spiral</td>
<td>23.7</td>
<td>69</td>
</tr>
<tr>
<td>ILT J122037.67+473857.6</td>
<td>0.059</td>
<td>FR I</td>
<td>Elliptical</td>
<td>22.9</td>
<td>51</td>
</tr>
<tr>
<td>ILT J124627.85+520222.1</td>
<td>0.067</td>
<td>FR I</td>
<td>Elliptical</td>
<td>23.6</td>
<td>76</td>
</tr>
<tr>
<td>ILT J125453.46+542923.4$^b$</td>
<td>0.069</td>
<td>FR I</td>
<td>Elliptical</td>
<td>22.6</td>
<td>18</td>
</tr>
<tr>
<td>ILT J130148.36+502753.3$^b$</td>
<td>0.120</td>
<td>FR I</td>
<td>Elliptical</td>
<td>23.5</td>
<td>55</td>
</tr>
<tr>
<td>ILT J145604.90+472712.1</td>
<td>0.087</td>
<td>FR I</td>
<td>Elliptical</td>
<td>25.1</td>
<td>62</td>
</tr>
</tbody>
</table>

$^a$ Host ID remains uncertain, $^b$ Sources subsequently identified as not being GSJ.
5.3 Observations

Using the nine sources I identified, a proposal for VLA observing time was submitted by my supervisor, J. Croston to observe the sources in both B and C configurations (see Section 3.2.1). As part of this proposal, I calculated the time on source that would be necessary to detect each source at a minimum threshold of 3σ. To do this I estimated the 3 GHz surface brightness for each source based on the 150 MHz LoTSS DR1 images and assuming the canonical spectral index of $\alpha = 0.7$. Using these results, I then derived the RMS noise necessary to detect the source at the required threshold and used the VLA exposure calculator\(^1\) to find the minimum observation time needed. Following the successful submission of the observing proposal I then planned the observing sessions, choosing the phase calibrators and dividing the allocated time between the calibrators and each of the nine sources.

All nine sources were observed in the S-band (2 - 4 GHz) using the VLA B configuration in order to map the sources at an angular resolution of $\sim 2.1$ arcseconds. Except for ILTJ125453 and ILTJ130148 which both have angular extents smaller than 30 arcseconds so that the B configuration captures all of their emission, S-band images were obtained using the VLA C-configuration for the remaining seven sources to map the full extended structure at a resolution of 7 arcseconds. This ensured that the VLA captured the largest angular scales where emission was observed by LoTSS DR1. The C-configuration observations were taken on 2018 November 18 and the B-configuration observations were taken on 2019 April 27. Both configurations used the flux density calibrator 3C 286 and were taken under project code: 18B-083. Details of both observations are given in Table 5.2.

Both sets of data were reduced as described in Section 3.3. Due to continuous Radio Frequency Interference (RFI) from satellite downlinks, all data in the 2.180-2.290 and 2.320-2.345 GHz ranges were flagged. Additional RFI flagging was done using the automated tfcrop and rflag routines as well as a manual check. Calibration was performed using a Perley & Butler (2017) model of the flux density calibrator, 3C 286, to determine the flux density scale. Images were made using the tclean algorithm with a multiscale deconvolver (Cornwell, 2008) and Briggs weighting with a robust parameter of 0.5 (Briggs, 1995). The signal to noise ratio for the sources is low, meaning that self-calibration did not improve image quality and so I omitted this stage in the final images. I combined the B and C-configuration images using the statwt task to compute the weightings of the images based on the RMS of the visibilities. The resulting images are shown in Figure 5.2.

The VLA image of ILTJ125453 (Figure 5.2) shows extended radio emission that is spatially correlated with the host suggesting a star-forming origin, though weak AGN activity is possible. The data also reveals a point source to the west of the galaxy centre. The location suggests this is not AGN-related and could be due to either a background source or a star-forming region within the host. The VLA does not show the elongated emission visible in the DR1 pre-release data (see Section 5.2) confirming the findings, using

\(^1\)https://obs.vla.nrao.edu/ect/
the LoTSS DR2 images, that this source is not a genuine GSJ. I do not consider this source any further.

Morphologically, the VLA images confirm the findings from the LoTSS DR2 images that ILTJ112543 and ILTJ121847 are FRII sources. Apart from ILTJ130148 where the VLA observes only a point source (see Section 5.4.3) and ILTJ122037 where no emission is detected, the VLA images also confirm that the remaining sources all appear FRI-like, though ILTJ145604 is somewhat borderline.

As described in Section 3.3.7, I calculated integrated flux density values using DS9 to visually trace a polygon around the edge of the emission and then using the `radioflux` tool\(^2\) to find both the flux density and RMS noise in the image. The images have an average RMS noise of 0.07 mJy and an average peak signal to noise ratio of 26. The final flux density error was found by combining the noise error in quadrature with the calibration uncertainty for the S-band, which is estimated at 5 per cent (Perley & Butler, 2017). I note that, within the error bounds, this gives the same flux density values as using CASA’s `imfit` function (also described in Section 3.3.7) to fit Gaussians to each separately identifiable emission region and aggregating the results. My error values are used in Sections 5.4 and 5.5 when comparing flux density values measured by different telescopes, but they are not used for the spectral index/ageing maps where, as described in Section 5.6, a weighted least squares method is used to calculate the errors for each pixel. The results are listed in Table 5.2.

For those sources where separate core and lobe components were visible in the VLA images I used the `radioflux` tool to measure the flux densities of each component. Using these data, I calculated spectral indices for each component allowing me to compare different regions from within the same image (see Section 5.5.2).

The source sizes in the LoTSS DR1 catalogue were derived from the ellipses used by the Python Blob Detector and Source Finder (Mohan & Rafferty, 2015). As discussed in Mingo et al. (2019), this tends to underestimate the size and flux densities of the smallest sources, such as GSJ. Rather than using the catalogued values, I therefore applied the method above to the LoTSS DR2 images finding flux densities for both the total source as well as for any sub-components. Errors were calculated as above using the calibration error for LoTSS which is conservatively estimated at 20 per cent (Shimwell et al., 2017). Applying this technique, I found flux densities for my sources that are 1 - 40 per cent higher than those listed in LoTSS DR1 with the majority being 10 - 20 per cent higher, confirming the findings of Mingo et al. (2019). Throughout this chapter I use the `radioflux` measured values.

### 5.3.1 WENSS and NVSS Data

To study the spectral properties of my GSJ sub-sample I combined the LoTSS and VLA data with 327 MHz and 1.4 GHz data from the Westerbork Northern Sky Survey (WENSS) (Rengelink et al., 1997) and NRAO VLA Sky Survey (NVSS) (Condon et al., 1998), taken

\(^2\)Available at [https://www.github.com/mhardcastle/radioflux](https://www.github.com/mhardcastle/radioflux)
<table>
<thead>
<tr>
<th>Source Name</th>
<th>Calibrator 1/2/3</th>
<th>Time (B/C)</th>
<th>Source Phase</th>
<th>PI</th>
<th>NSS</th>
<th>WENSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILTJ112543</td>
<td>J1137+6211(C)</td>
<td>7.7 ± 0.39</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>26 ± 0.1 × 10 2</td>
<td>138 ± 40 ± 9.9 2</td>
<td>1438+6211(C)</td>
</tr>
<tr>
<td>ILTJ120326</td>
<td>J1219+4829</td>
<td>4.4 ± 0.23</td>
<td>1.1 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>0.33 ± 0.03 0.1 3</td>
<td>1119 ± 4829</td>
</tr>
<tr>
<td>ILTJ120645</td>
<td>J1219+4829</td>
<td>2.8 ± 0.15</td>
<td>1.1 ± 0.1 × 1.0 2</td>
<td>10 ± 0.1 × 10 2</td>
<td>0.31 ± 0.03 0.1 3</td>
<td>1119 ± 4829</td>
</tr>
<tr>
<td>ILTJ121847</td>
<td>J1219+4829</td>
<td>3.7 ± 0.20</td>
<td>1.1 ± 0.1 × 1.0 2</td>
<td>12 ± 0.1 × 10 2</td>
<td>0.23 ± 0.03 0.1 3</td>
<td>1119 ± 4829</td>
</tr>
<tr>
<td>ILTJ122037</td>
<td>J1219+4829</td>
<td>7.1 ± 0.36</td>
<td>1.1 ± 0.1 × 1.0 2</td>
<td>18 ± 0.1 × 10 2</td>
<td>0.34 ± 0.03 0.1 3</td>
<td>1119 ± 4829</td>
</tr>
<tr>
<td>ILTJ124627</td>
<td>J1219+4829</td>
<td>7.7 ± 0.36</td>
<td>1.1 ± 0.1 × 1.0 2</td>
<td>12 ± 0.1 × 10 2</td>
<td>0.34 ± 0.03 0.1 3</td>
<td>1119 ± 4829</td>
</tr>
<tr>
<td>ILTJ125453</td>
<td>J1219+4829</td>
<td>5.8 ± 0.03</td>
<td>1.1 ± 0.1 × 1.0 2</td>
<td>10 ± 0.1 × 10 2</td>
<td>0.51 ± 0.03 0.1 3</td>
<td>1119 ± 4829</td>
</tr>
<tr>
<td>ILTJ130148</td>
<td>J1219+4829</td>
<td>2.0 ± 0.04</td>
<td>1.1 ± 0.1 × 1.0 2</td>
<td>10 ± 0.1 × 10 2</td>
<td>0.53 ± 0.03 0.1 3</td>
<td>1119 ± 4829</td>
</tr>
<tr>
<td>ILTJ145604</td>
<td>J1438+4739</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ145418</td>
<td>J1438+4739</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ151633</td>
<td>J151633</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ151817</td>
<td>J151817</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ152031</td>
<td>J152031</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ152537</td>
<td>J152537</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ152933</td>
<td>J152933</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ153515</td>
<td>J153515</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ153928</td>
<td>J153928</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ154331</td>
<td>J154331</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ154733</td>
<td>J154733</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
<tr>
<td>ILTJ155138</td>
<td>J155138</td>
<td>138 ± 9.92</td>
<td>1.0 ± 0.1 × 1.0 2</td>
<td>20 ± 0.1 × 10 2</td>
<td>1438+4739</td>
<td></td>
</tr>
</tbody>
</table>

Sources subsequently identified as not being GS1.
using the Westerbork and VLA telescopes respectively. The maximum positional uncertainty for faint sources is 7 arcsec in NVSS and 5 - 10 arcsec in WENSS. To account for this I used a 20 arcsec radius when cross-matching with both catalogues. Table 5.2 lists the catalogue IDs for those sources where a match was found.

WENSS has a 54 arcsec angular resolution with a sensitivity of 18 mJy whilst NVSS has a 45 arcsec angular resolution with a sensitivity of 2.5 mJy. The large beam sizes of these surveys (relative to the LoTSS and VLA images) mean it is possible that there is contamination from secondary sources. I therefore examined images from the LoTSS survey but found that none of my sources have secondary sources close enough to affect either the NVSS or WENSS catalogued values.

5.4 Optical Hosts

One of the reasons for obtaining the high angular resolution VLA images (Figure 5.2) was to verify the optical host listed in the LoTSS DR1 value added catalogue. The VLA data shows a radio core located within 0.15 arcsec of the centre of the host galaxy, confirming the host ID as well as an AGN core for three of my sources:

- ILTJ120326
- ILTJ120645
- ILTJ124627

One of the sources, ILTJ122037, was undetected by the VLA, meaning that the host ID could not be confirmed, though in this particular case I am happy to retain the source as the LoTSS image leaves little doubt the host has been correctly identified. The remaining four sources are all considered individually below.

5.4.1 ILT J112543.06+553112.4

The VLA contours for this source appear as two disconnected islands of radio emission, one to the north west and the other to the south east. There is no observable radio core. Most easily seen using the B-configuration VLA data (Figure 5.3), the northern island contains what appears to be a bright hot spot, whilst the southern island has a less pronounced hot spot confirming the FRII nature of this source. The hotspot in the north west lobe has a surface brightness approximately 25 per cent brighter than the hotspot in the south east. Whilst the centre of the LoTSS-identified host galaxy is significantly closer to the north east lobe, it does lie directly along the line joining the two hotspots.

The FRII nature of the source leaves no doubt that the radio emission is caused by an AGN. The observed asymmetries in jet lengths and lobe morphology could be attributable to asymmetries in the host environment through which the jets have passed (Wagner & Bicknell, 2011; Gaibler, 2014) or to orientation (see for example Harwood et al., 2020).
Figure 5.2: Each image shows LoTSS DR2 contours in gold and VLA S-band contours from the combined B and C configuration images in white on top of the Pan-STARRS r-band optical image. Each image has the VLA beam in the bottom left and a scale bar in the bottom right. Radio contours are shown at $3 \times 2''$ times the local RMS where $n \in \{0, 0.5, 1.0, \ldots\}$. 
Figure 5.2: (continued)
Figure 5.3: The source ILTJ112543 as imaged by the VLA in B-configuration. The RMS is 0.012 mJy beam$^{-1}$, the VLA beam is shown in the bottom left and a scale bar in the bottom right. The position of the optical host is indicated by the white cross. A bright hotspot can be seen in the north west with a fainter hotspot visible in the south east lobe.
Asymmetries in jet lengths are not uncommon in FRII radio galaxies (e.g. Mullin et al., 2008).

As discussed in Section 4.3.1, the absence of a detected radio core means that this may be a chance line of sight effect, with the true host remaining unseen in the background. However, the absence of an alternative host means that the LoTSS DR1 host ID remains plausible.

5.4.2 ILT J121847.41+520128.4

The VLA radio contours for this source show a peak ‘core’ emission lying on a line joining the two lobes. The ‘core’ is offset from the host galaxy centre where an AGN would most likely be located by $\sim 1.4$ arcsec suggesting that the host may have been misidentified. The ‘core’ is also not the Gaussian shape typically associated with radio cores, being slightly elongated and extending to the south west of the host.

I therefore investigate the possibility that the offset ‘core’ is not AGN related and is due entirely to star formation activities. Using a spectral index of $\alpha = 0.7$ to convert the 1.4 GHz Radio-SFR relation of Gurkan et al. (2018) to 3 GHz results in the relation:

$$\log_{10}(L_{3 \text{ GHz}}) = 0.87 \pm 0.01 \times \log_{10}(\Psi) + 21.09 \pm 0.03$$

(5.1)

where $\Psi$ is the star formation rate in solar masses per year. According to this relation, the largest SFR published in SDSS-DR14, calculated at 97.5 per cent of the probability distribution and derived using the methods of Brinchmann et al. (2004), would result in a 3 GHz radio luminosity of $\log_{10}(L_{3 \text{ GHz}}) = 21.92 \pm 0.04$ W Hz$^{-1}$. Lower star formation rates give even lower predicted radio luminosities, all of which are less than the observed $22.56 \pm 0.02$ W Hz$^{-1}$ seen in the core region.

Therefore, assuming all the observed ‘core’ flux comes from the host galaxy, star formation alone cannot account for the observed emission, suggesting an AGN is present. This is reinforced by the elongated shape extending only to the south as, if this were due to star-forming winds, a similar extension to the north would be expected. I therefore consider other explanations for the observed morphology.

One possible explanation would be if the host galaxy were moving through a relatively dense environment causing bending of the underlying jets and elongation of the central core. Using the group catalogue of Tempel et al. (2014), the host is the second most luminous galaxy in a small group of 4, situated at an approximate distance of 0.2 Mpc from the brightest group galaxy. Such a small group would imply an extremely sparse environment suggesting this is not the cause of the elongated emission.

As discussed in Section 4.3.2, an alternative possibility that cannot be discounted is that ILTJ121847 is involved in a galaxy merger. Whilst this would explain the orientation of the jets, there is no suggestion in the PanSTARRS images of a secondary galaxy, though it may be obscured by the foreground host. If correct, the redshift of the two galaxies would be the same and so the GSJ nature of the source would remain.
Also discussed in Section 4.3.2, since spiral-hosted radio galaxies are extremely rare, it remains possible that the host has been misidentified and that the true host is an unseen background galaxy. Since no secondary galaxy is seen, the PanSTARRS limiting apparent magnitude of 24 means that the secondary galaxy would have to be extremely faint and/or obscured by the foreground galaxy. In this scenario it is also possible that the foreground galaxy also contains either a weak AGN and/or star formation related radio emission that is resulting in the elongated radio emission of the core region. For the remainder of the paper I continue to consider this source as a GSJ, but note that future, deeper optical/IR images may identify alternative potential hosts.

5.4.3 ILT J130148.36+502753.3

The image shown in Figure 5.2 shows a large foreground galaxy identified as the host by the LoTSS DR1 survey with a smaller object located to the north-east about which the VLA has detected strong emission. The VLA data does not show any emission coming from the host identified by LoTSS. The emission observed by the VLA does not appear to be jetted in nature.

I could not find any entry for the source of the VLA emission in either NED or SIMBAD. SDSS does detect the source of the VLA emission, though the pipelines used to find spectroscopic and photometric redshifts failed for this object. PanSTARRS also detects this source, though photometric redshifts are not yet available. It is therefore unclear whether the source of the VLA emission is a background galaxy or quasar, a satellite of the larger galaxy or even a bright component of the larger galaxy.

Irrespective of the true nature of the source of the VLA emission, it seems likely that at least some of the emission seen by LOFAR is due to this source. Equally, the elongated morphology of the emission seen by LOFAR, combined with the lack of any peak at the location of the VLA emission suggests that at least some of the emission seen by LOFAR is caused by activity in the foreground galaxy with the relative contributions of the two sources being impossible to distinguish. Whilst it remains possible there is galaxy-scale jet behaviour in the LoTSS-catalogued source, the uncertainty in the GSJ nature of this source means that I do not consider it any further.

5.4.4 ILT J145604.90+472712.1

Although the VLA image does not show a radio core for this object, it does still show two separate regions of emission emanating to the west and east of the host galaxy consistent with jetted activity. The core location from which these two regions of radio emission originate is consistent with the host identification and so I am confident that the host has been correctly identified and that this is a GSJ.
Table 5.3: The integrated spectral index for my sources (excluding the two non-GSJ sources) using the 150 MHz LoTSS and 3 GHz VLA observations. * Host ID remains uncertain.

<table>
<thead>
<tr>
<th>Source Name</th>
<th>$\alpha_{150\text{ MHz}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILTJ112543$^a$</td>
<td>$1.0 \pm 0.1$</td>
</tr>
<tr>
<td>ILTJ120326</td>
<td>$0.4 \pm 0.1$</td>
</tr>
<tr>
<td>ILTJ120645</td>
<td>$0.8 \pm 0.1$</td>
</tr>
<tr>
<td>ILTJ121847$^a$</td>
<td>$0.9 \pm 0.1$</td>
</tr>
<tr>
<td>ILTJ122037</td>
<td>$&gt; 2.4$</td>
</tr>
<tr>
<td>ILTJ124627</td>
<td>$0.5 \pm 0.1$</td>
</tr>
<tr>
<td>ILTJ145604</td>
<td>$0.6 \pm 0.1$</td>
</tr>
</tbody>
</table>

5.5 Spectral Indices

5.5.1 Integrated Spectra

In order to characterise the bulk properties of the radio emission, compare my sources to other samples of radio galaxies and confirm the findings of Section 4.4.1.2, I applied the methods described in Section 3.3.8 to derive the integrated 150 MHz to 3 GHz spectral indices. For all my sources, the angular sizes of the detected LOFAR structures are smaller than the largest angular scales that the VLA observations are sensitive to and so these results are expected to be robust. The integrated spectral indices are listed in Table 5.3.

ILTJ122037 is undetected in the VLA observations and so, using three times the RMS as the detection threshold, an upper limit is given. This source has an integrated spectral index far steeper than the criterion of 1.2 traditionally used to identify remnant sources (e.g. Brienza et al., 2017; Cohen et al., 2007; Parma et al., 2007). The steep spectral index, combined with the lack of any visible core in the LoTSS data, shows that this is a remnant source. According to the group catalogue of Tempel et al. (2014), this source is located within a group of 9 galaxies, suggesting a low-density environment. Since remnant sources outside of cluster environments are extremely rare (Brienza et al., 2016) this is a particularly interesting object.

Another object, ILTJ120326 has a spectral index below the value of 0.5 typically used to identify flat spectra. When observed with the VLA, this source has comparatively weak radio emission coming from the lobes (Figure 5.2) with over 75 per cent of the total flux density coming from the core (over 45 per cent when viewed with LOFAR). As a result its integrated spectra, particularly at higher frequencies, is dominated by the core region. The core-dominance and flat spectra indicate that this source is strongly affected by absorption; either free-free absorption (FFA) or synchrotron self-absorption (SSA) (O’Dea & Saikia, 2021).

All the other sources in my sample have integrated spectral indices that are typical of larger radio galaxies (for example the 3CRR sample of Laing et al., 1983), confirming the findings of Chapter 4.

I also wish to see how the integrated spectral index varies with frequency and whether there is any low frequency flattening as would be expected for compact sources. To do
this I compared the radio flux densities from the LoTSS, WENSS and NVSS catalogues (where available) with the values derived from the VLA images. Measured using the LoTSS images, ILTJ12543 has the largest angular size of all my sources at 70 arcsec, this is substantially less than the maximum angular scale of NVSS (20 arcmin) and WENSS (over 1°) so that spatially these surveys can observe all the flux seen by LOFAR. However, the WENSS and NVSS surveys are less sensitive and may not be detecting all of the fainter flux density associated with a source, potentially causing the reported total flux densities to be underestimated, though no allowance is made for this.

The results are shown in Figure 5.4. The NVSS errors shown are those reported by the survey and the WENSS errors are calculated using the methods of Rengelink et al. (1997). The errors for the LoTSS and VLA images were calculated as described in Section 5.3. ILTJ122037 is not detected in either the NVSS or WENSS catalogues or in my new VLA observations and is therefore not shown.

As can be seen in Figure 5.4, there is no evidence of significant low-frequency flattening in any of my sources indicating that the turnover, if present, must be at lower frequencies. For the majority of my sources the spectral index is relatively constant over the measured frequency range showing little deviation from the 3 GHz to 150 MHz measured integrated spectral index. The spectra are therefore similar to those of larger radio galaxies, not compact sources.

5.5.2 Component Spectra

The 3 GHz VLA image of ILTJ120645 (Figure 5.2) clearly shows a pronounced radio core. However, no radio core is seen in the 150 MHz LoTSS image. This difference in the spectral behaviour of the core is seen in another GSJ, NGC 3801 (Heesen et al., 2014), and is also identical to larger radio galaxies which have flat core regions (e.g. Simpson, 2017; Morganti et al., 1997).

For the three GSJ within the sample that have separately identifiable lobes and cores in both the LoTSS and VLA images, ILTJ120326, ILTJ121847 and ILTJ124627, I calculated the spectra of the lobe and core sub-components, using the same technique as described in Section 5.3 to calculate the flux densities for both LoTSS and VLA images. In each case I found significant differences between the lobes and cores, again indicating different physical properties in these regions.

5.6 Spectral Index Maps

Apart from ILTJ122037, the other six sources identified in Table 5.3 all have extended emission in both the LoTSS DR2 and VLA images. For these sources I produced spatially resolved spectral index maps that would then allow me to identify any structure within my sources. This was done using the Broadband Radio Astronomy Tools\(^3\) (BRATS) (Harwood

\(^3\)http://www.askanastronomer.co.uk/brats/
Figure 5.4: Plot of the total measured flux density against frequency for each source. Shown against each line are the corresponding spectral indices. Stars represent LoTSS measurements, squares WENSS, circles NVSS and crosses VLA. WENSS and NVSS are less sensitive than the other surveys, possibly causing their flux densities to be underestimated (see text for details).
et al., 2013, 2015) as described in Section 3.3.10. The spectral maps produced are shown in Figure 5.5.

The spectral index error maps are calculated by BRATS using a weighted least squares method (see Harwood et al., 2015, for details). They show increased uncertainties towards the edge of the emission with some sources showing high uncertainties at the very edge of the observed emission. However, overall the spectral index errors are low across the majority of the observed emission and most spectral structure shown is on resolved scales and showing gradients in the sense expected for typical radio-galaxy structures indicating that the spectral index maps are reliable except, in some cases, for the outer few pixels.

Outside of the core/hotspot emission (where visible), my sources show only a small amount of variation in the spectral index across the majority of the extended emission which is not surprising given the fairly low angular resolution. As expected of FRII sources, the spectral gradients that can be observed for ILTJ112543 and ILTJ121847 become overall progressively steeper with distance from the hotspot. Similarly, the FRI sources show a general trend for the spectral index to increase with distance away from the core.

Although obeying this general trend, the eastern jet of ILTJ124627 does have two regions of flat spectral index at the tip and midway along the jet. This is discussed further in Section 5.7.3. The spectral index maps also show the different core spectral behaviour for ILTJ120326 and ILTJ121847 mentioned in Section 5.5.2. Though less obvious, the core of ILTJ124627 also shows a different core spectral behaviour with a slightly flatter spectral index than the surrounding regions.

## 5.7 Spectral Model Fitting

For the six sources with extended emission in both the LoTSS DR2 and VLA images I fitted spectral models to find the age of the radio emission. When fitting spectral models, in order to constrain the spectral ages as much as possible, I divided my matched VLA images (described in Section 5.6) into four frequency ranges each of 500MHz bandwidth, using the resulting images along with the 150 MHz LoTSS data to perform the model fitting.

As described in Sections 5.5.2 and 5.6, the cores of some of my sources have significantly different spectral behaviour from the lobes. Since I am interested in the age of the lobes, I follow the methodology of Heesen et al. (2014) and exclude the cores from all four sources where the core region could be identified to eliminate any adverse effects they would have upon the model fitting.

Following the methodology described in Section 3.3.11, I used BRATS to fit Jaffe-Perola (JP) models (Jaffe & Perola, 1973) to my data. Using the JP model allows a direct comparison with the few previous spectral ageing studies of GSJ (e.g. Parma et al., 1999; Heesen et al., 2014). Along with the radio images, the other inputs required for spectral age modelling are the magnetic field strength and the injection index, described in Sections 5.7.1 and 5.7.2 respectively. My results are summarised in Table 5.4. The
Figure 5.5: Left column shows the 150 MHz - 3 GHz spectral index maps and the right column shows the associated error maps. The errors presented are those used for the spectral ageing analysis and include flux density calibration errors. The LOFAR beam is shown in the bottom left and a scale bar in the bottom right.
Figure 5.5: (Continued) Left Column shows the 150 MHz - 3 GHz spectral index maps and the right column shows the associated error maps. The errors presented are those used for the spectral ageing analysis and include flux density calibration errors. The LOFAR beam is shown in the bottom left and a scale bar in the bottom right.
resulting images are shown in Figures 5.6 to 5.11 inclusive with the results discussed in Section 5.7.3.

5.7.1 Magnetic Field Strengths

The strength of the magnetic field in the lobes was calculated using PySYNCH as described in Section 3.3.9. This was initially done under equipartition energy conditions assuming no non-radiating particles (listed as $B_{eq}$ in Table 5.4). The size and flux densities of the lobes was taken from the VLA images. I note that similar magnetic field strengths were obtained using the LoTSS images.

While I considered the case of equipartition field strengths assuming no non-radiating particles, I also considered more physically realistic scenarios for both FRI and FRII sources based on the conclusions of X-ray studies. For FRII-type jets independent measurements of the magnetic field strength using X-ray observations have found the average magnetic field strength is $\sim 0.4B_{eq}$ (Ineson et al., 2017), where $B_{eq}$ is the equipartition magnetic field strength assuming no proton content.

For FRIIs the lack of inverse Compton X-ray detection means the magnetic field strengths are less well constrained. However, using equipartition estimates with no proton content, it has been shown that the internal lobe pressure is insufficient to balance the external medium. The extra pressure is believed to come from either entrained material, higher magnetic field strengths or a combination of both (Croston et al., 2003, 2008a; Croston & Hardcastle, 2014). Recently, for a population of 27 FRIs, Croston et al. (2018) found that in order to achieve pressure balance, where the magnetic field and total (radiating and non-radiating) particle energy densities are in equipartition, a ratio of $\sim 10$ for the non-radiating to radiating particle energy density was required.

Therefore in the discussion that follows I adopt magnetic field strength values (i) for the FRIs assuming equipartition between the magnetic and total particle energy densities with a ratio between the non-radiating and radiating particle energy density of 10 and (ii) for the FRIIs using magnetic field strengths that are 0.4 times the equipartition magnetic field strengths calculated assuming no proton content. These adjusted values are given as $B_{adj}$ in Table 5.4. In the following discussion I also note how my conclusions would differ for the assumption of equipartition with no non-radiating particles in both cases.

5.7.2 Injection Indices

The injection indices, shown in Table 5.4, were all calculated using the findinject function in BRATS, as described in Section 3.3.10. I note these values were the same no matter how the magnetic field strengths were calculated. The majority of the sources have injection indices within the range 0.5 to 0.7 typically assumed for radio loud AGN. The injection indices are also consistent with those found for the B2 sample of radio galaxies which are a mix of FRI and FRII radio galaxies covering a range of luminosities and physical sizes, the lower end of which are similar to the sample of GSJ (Parma et al., 1999). The injection
indices are also similar to the value of $0.5 \pm 0.05$ found for another GSJ, NGC 3801 (Heesen et al., 2014).

However, ILTJ112543 and ILTJ121847, the two FRII spirals, both have steeper injection indices closer to 0.8. These sources support the argument that FRIIs have steeper injection indices than previously thought (Harwood et al., 2016, 2017). Models have suggested a steeper injection index should equate to more powerful jets (Konar & Hardcastle, 2013) but, as can be seen in Table 5.2, the two FRIIs are amongst the least luminous in my sample. Whilst this, again, suggests that the hosts for these sources have been misidentified, this is not conclusive as, whilst they cannot rule the model of Konar & Hardcastle (2013) out, Harwood et al. (2016) do find two FRIIs whose hotspots, according to the model, imply a flatter injection index than is found, suggesting other factors also need to be considered.

### 5.7.3 Spectral Ages

The spectral ages shown in Table 5.4 and presented in Figures 5.6-5.11 were calculated using BRATS as described in Section 3.3.11. The magnetic field strengths and injection indices were calculated as explained above. The FRIs in my sample are young sources with maximum ages between 5 and 20 Myr, whilst the FRIIs are older with ages between 40 and 60 Myr. I note that, for the FRIs, using equipartition field strengths (with no proton content) approximately doubles the age estimates. Similarly for the FRIIs, using equipartition field strengths approximately halves the ages listed.

None of the models fitted by BRATS can be rejected at even the 68 per cent confidence level indicating that the models are a good fit to the data. The reduced $\chi^2$ maps along with average reduced $\chi^2$ values of about unity for three degrees of freedom in each case (see Table 5.4) also confirm that the models are a good fit. However, some of the absolute errors are quite large. This is due to the large LOFAR errors and the lack of variation in the spectral index as a function of frequency observed for all of my sources (Figure 5.4) meaning that higher frequency data, where spectral curvature is most easily constrained, is needed to reduce the model errors.

As expected, the regions of flatter spectral index are associated with the youngest spectral ages. Consequently, where errors are fairly well constrained, the gradients in spectral index noted in Section 5.6 are mirrored in the spectral ages.

Also noted in Section 5.6 were the anomalous regions of flat spectral indices in the eastern jet of ILTJ124627, which are now seen as an extended region of low spectral age (Figure 5.10). This source has background galaxies visible in the optical image that overlap with the radio emission (Figure 5.2). Whilst there is no indication that these galaxies are emitting at radio frequencies, there is a prominent background galaxy midway along the eastern lobe that may be associated with the region of low age plasma observed. Overlaying the position of the background host on the spectral age map (Figure 5.12), it can be seen that the galaxy lies between and slightly below the region of low spectral age.
### Table 5.4: Summary of the results of the spectral age fitting.

$B_{eq}$ is the equipartition magnetic field strength assuming no non-radiating particles, $B_{adj}$ are the adjusted magnetic field strengths used within this work to better represent the conditions of FRI/FRII galaxies (see text for details). Ages shown were calculated using the adjusted magnetic field strengths. * Host ID remains uncertain.

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Injection Index</th>
<th>$B_{eq}$ / T</th>
<th>$B_{adj}$ / T</th>
<th>Average Age / Myr</th>
<th>Minimum Age / Myr</th>
<th>Maximum Age / Myr</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILTJ114627</td>
<td>0.45</td>
<td>1.21 x 10^{-9}</td>
<td>4.81 x 10^{-10}</td>
<td>1.41 x 10^{-9}</td>
<td>8.42 x 10^{-10}</td>
<td>8.22 x 10^{-10}</td>
</tr>
<tr>
<td>ILTJ120645</td>
<td>0.49</td>
<td>1.19 x 10^{-9}</td>
<td>2.93 x 10^{-10}</td>
<td>1.07</td>
<td>0.47</td>
<td>0.47</td>
</tr>
<tr>
<td>ILTJ121545a</td>
<td>0.78</td>
<td>6.00 x 10^{-10}</td>
<td>4.00 x 10^{-10}</td>
<td>0.79</td>
<td>0.00</td>
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<tr>
<td>ILTJ124627</td>
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<td>0.87</td>
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<tr>
<td>ILTJ121545a</td>
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<td>4.98 x 10^{-10}</td>
<td>0.87</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ILTJ121545a</td>
<td>0.78</td>
<td>16.97 x 10^{-9}</td>
<td>16.97 x 10^{-9}</td>
<td>20.65 + 4.21</td>
<td>11.52 + 6.18</td>
<td>11.52 + 6.18</td>
</tr>
</tbody>
</table>

$B_{eq}$ is the equipartition magnetic field strength assuming no non-radiating particles, $B_{adj}$ are the adjusted magnetic field strengths used within this work to better represent the conditions of FRI/FRII galaxies (see text for details). Ages shown were calculated using the adjusted magnetic field strengths. * Host ID remains uncertain.
5.7. Spectral Model Fitting

Figure 5.6: Results of the spectral fitting for ILTJ112543. Top left shows the spectral age map and top right shows the reduced $\chi^2$ for the spectral age map. Bottom left and right images show the positive and negative errors for the spectral age map. The LOFAR beam is shown in the bottom left of each image and a scale bar in the bottom right.
Figure 5.7: Results of the spectral fitting for ILTJ120326. Top left shows the spectral age map and top right shows the reduced $\chi^2$ for the spectral age map. Bottom left and right images show the positive and negative errors for the spectral age map. The LOFAR beam is shown in the bottom left of each image and a scale bar in the bottom right.
5.7. Spectral Model Fitting

Figure 5.8: Results of the spectral fitting for ILTJ120645. Top left shows the spectral age map and top right shows the reduced $\chi^2$ for the spectral age map. Bottom left and right images show the positive and negative errors for the spectral age map. The LOFAR beam is shown in the bottom left of each image and a scale bar in the bottom right.
Figure 5.9: Results of the spectral fitting for ILTJ121847. Top left shows the spectral age map and top right shows the reduced $\chi^2$ for the spectral age map. Bottom left and right images show the positive and negative errors for the spectral age map. The LOFAR beam is shown in the bottom left of each image and a scale bar in the bottom right.
5.7. Spectral Model Fitting

Figure 5.10: Results of the spectral fitting for ILTJ124627. Top left shows the spectral age map and top right shows the reduced $\chi^2$ for the spectral age map. Bottom left and right images show the positive and negative errors for the spectral age map. The LOFAR beam is shown in the bottom left of each image and a scale bar in the bottom right.
Figure 5.11: Results of the spectral fitting for ILTJ145604. Top left shows the spectral age map and top right shows the reduced $\chi^2$ for the spectral age map. Bottom left and right images show the positive and negative errors for the spectral age map. The LOFAR beam is shown in the bottom left of each image and a scale bar in the bottom right.
5.7. Spectral Model Fitting

The astrometric uncertainties for LOFAR and the VLA are too small to account for the difference and so the background galaxy cannot be responsible for this low age plasma.

All FRIIs previously studied using BRATS exhibit anomalous, non-physical regions showing zero ages. Harwood et al. (2015) argue that this may be due to performing spectral modelling at high angular resolutions on high dynamic range sources. Although not associated with FRII sources, the regions we observe in ILTJ124627 and at the tip of the southern lobe of ILTJ120326 may have a similar non-physical origin. I also note that these regions are associated with large positive errors and so may not be anomalous at all. However, I cannot discount the possibility that these regions are real and may be caused either by a region of enhanced particle acceleration within the jet and/or some interaction with the surrounding environment.

Figure 5.12: Spectral age map for ILTJ124627 with the position of the background galaxy on the eastern lobe marked by the black circle. The LOFAR beam is shown in the bottom left and a scale bar in the bottom right.
5.8 Average Advance Speeds

I also estimated the average expansion speed for the lobes of each of my sources in order to see whether they could be expanding fast enough to shock the local environment. The standard methodology of Alexander & Leahy (1987) involves dividing the lobes into separate regions and estimating the speed based on the average age and separation distance of each region. However, the small size of the sources meant that this method resulted in between one and a maximum of three data points per source lobe.

Many of the sources also show very little variation in spectral age across large portions of the lobes. This may be due to the angular resolution of the images with different electron populations being caught within a single beam or it may be due to physical mixing of electron populations within the sources themselves (Turner et al., 2018). Regardless of the cause, the low variation in spectral age meant that applying the techniques of Alexander & Leahy (1987) resulted in unreliable estimates.

I therefore use the same methodology as Harwood et al. (2013, 2015) where the lobe advance speed is found by dividing the source size by the age of the oldest plasma. For the FRI sources I assume that the oldest observed plasma was produced when the jet first became active and so I use the distance from the host to the edge of the observable emission as the source size. For the FRII-like sources I assume the oldest emission was produced at a time when the hot spot was located where the plasma is currently seen and so take the distance between the hot spot and the location of the oldest observed plasma as the source size.

The results are shown in Table 5.5 where I also express the results in terms of the local sound speed, which I assume to be 400 km s$^{-1}$ (the approximate speed of sound in the ISM at a temperature of 0.6 keV, typical of the sparse groups in which, as discussed in Section 4.4.3, GSJ reside). For the FRIIs in my sample I find significantly sub-sonic advance speeds. For the FRIs the lobe advance speeds are supersonic. In comparison, using equipartition magnetic field strengths with no protons, this result is unchanged for the FRIIs where the lobe advance speeds become 0.2 - 0.5$c_s$, whilst for the FRIs the advance speeds become mildly supersonic with speeds of 1.3 - 2.8$c_s$.

It is well-established that spectral ages are typically lower than the corresponding dynamical ages (Eilek, 1996), a result that has been confirmed using the high spectral resolution of BRAT’S (Harwood et al., 2013). Using the BRAT’S software Harwood et al. confirmed that dynamical ages can be up to 10 times more than the corresponding spectral age. It is therefore possible that my age estimates are too low so that my speed estimates should be considered as upper limits.

However, Blundell & Rawlings (2000) note that for young radio sources with a dynamical age less than 10 Myr, spectral age fitting may be more accurate. If correct, this means that the ages, and hence lobe advance speeds, of the FRIs in my sample are, as a first-order estimate, reliable. For FRIIs, Mahatma et al. (2020) found that the discrepancy between spectral and dynamic ages can be as low as a factor of ~ 2 when using sub-equipartition
<table>
<thead>
<tr>
<th>Source Name</th>
<th>Emission type</th>
<th>LOFAR Length of radio lobe (km)</th>
<th>Oldest Plasma Age (Myr)</th>
<th>Average Advance Speed (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILTJ112543(W)</td>
<td></td>
<td>2.9</td>
<td>18.3</td>
<td>3.7</td>
</tr>
<tr>
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<td></td>
<td>1.6</td>
<td>25.4</td>
<td>2.9</td>
</tr>
<tr>
<td>ILTJ120326(S)</td>
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<td>23.4</td>
<td>108.3</td>
<td>33.4</td>
</tr>
<tr>
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<td>15.9</td>
<td>135.0</td>
<td>11.5</td>
</tr>
<tr>
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<td>178.7</td>
<td>10.0</td>
</tr>
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<td>108.3</td>
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</tr>
<tr>
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<td>2.9</td>
<td>25.4</td>
<td>2.9</td>
</tr>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>ILTJ145604(E)</td>
<td></td>
<td>1.6</td>
<td>2623.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 5.5: The oldest plasma ages and distances used to calculate the average lobe advance speeds for all sources analysed with BRATS. * Host ID remains uncertain.
magnetic fields (such as those used in this study). If correct this once again implies that
the ages, and hence lobe advance speeds, of my FRIIs are reliable.

5.9 Discussion

5.9.1 Remnant GSJ

ILTJ112543 and ILTJ121847, the two FRII spiral-hosted sources, have spectral indices
towards the steeper end of the range of values found for the 3CRR sample (Laing et al.,
1983). Though not atypical of spectral indices found for larger AGN, recent studies have
shown that these values are intermediate between sources typically classed as active and
remnant AGN (Mahatma et al., 2018). Therefore, the possibility that these are remnant
sources must be considered.

Like remnant sources, ILTJ112543 has no observable radio core. However, the lobes do
not show the relaxed structure often seen in remnant sources and a bright hotspot is visible
in the north west lobe with a fainter hotspot in the south east. Though the possibility
of ongoing activity from a weak core cannot be excluded, it is possible that this source
may have recently switched off so that the core is no longer visible but previously emitted
material is still fuelling the hotspots (Tadhunter, 2016a). If correct, and assuming the host
has been correctly identified, the short distances from the core to the hotspots (3.4 and
7.2 kpc to the North and South respectively) suggest this source may be an interesting
example of a spiral AGN that has only very recently turned off.

For ILTJ121847, the 150 MHz to 3 GHz spectral index of the core is 0.72 ± 0.09
consistent with ongoing AGN activity (e.g. Laing et al., 1983; Sabater et al., 2019). This,
combined with the morphological evidence suggesting the core of this source is a mix of
AGN and star formation related emission (Section 5.4.2), means I do not believe this is a
remnant source.

Unlike the two spiral-hosted sources, the extremely steep spectral index of ILTJ122037
means this is definitely a remnant source (Murgia et al., 2011; Mahatma et al., 2018) with
the lack of detection in the 3 GHz VLA images lending tentative support to the idea that
remnant sources fade quickly (Kaiser & Cotter, 2002; Mahatma et al., 2018). The small
scale of the emission seen by LOFAR makes this the first known source with remnant
emission of a similar size to the host. Whilst LOFAR is expected to be able to detect
a large fraction of remnant sources, the outward diffusion of electrons means they are
expected to be physically large (e.g. Hardcastle et al., 2016), making the small size of this
source unusual. Whilst I cannot directly measure the age of the source, the fact that this
source never grew to large sizes does imply the radio jets were active for only a short period
of time, consistent with expectations for low mass systems (Heckman & Best, 2014).

Like the two FRII spiral-hosted sources, ILTJ122037 does not have the morphologi-
cally relaxed appearance typical of remnant sources (Brienza et al., 2016; Morganti, 2017).
Plotting this source on a BPT diagram shows ongoing AGN activity which, combined with
5.9. Discussion

the emission still having the appearance of being jet-related, means it is possible that this source has recently changed accretion mode, causing the radio jets to turn off.

Harcastle & Krause (2013) showed that for large radio galaxies, half of the total energy transported by the jets would still be present in the lobes at the moment the jets turn off. Assuming a similar fraction applies to smaller sources this would mean that half of the energy transported by ILTJ122037 has already been transferred to its environment. Given the small physical size of the remnant this energy must have been transferred into its local environment supporting the conclusion of Chapter 4 that GSJ are capable of having a significant impact upon the evolution of their hosts.

5.9.2 Source Ages

Parma et al. (1999) found the ages for a representative sample of 42 sources drawn from the B2 catalogue with 1.4 GHz luminosities between $10^{23}$ and $10^{25}$ W Hz$^{-1}$. These sources are predominantly FRI galaxies, though several FRII galaxies are also present. They found spectral ages ranging from 4 to 112 Myr with most being a few tens of Myrs old. The FRIs in my sample have maximum ages between about 5 and 20 Myr, consistent with the smaller, least luminous galaxies within the Parma et al. sample which are also comparable in size and luminosity to the largest most luminous GSJ. The FRI sources can be considered as young radio galaxies. These sources are comparable in age to the 10 kpc GSJ, NGC 3801, that was found to have a spectral age between 1.8 and 2.4 Myr (Heesen et al., 2014).

In contrast the FRIIs are older, both having maximum ages between 40 and 60 Myr. All my sources are older than the typical age of the compact CSS/GPS sources which typically have ages up to a few thousand years (O’Dea & Saikia, 2021). The size and age of my sources are therefore consistent with their being located along an evolutionary path joining CSS/GPS sources and larger radio galaxies. Overall, my sources are consistent with the trend seen by Parma et al. (1999) suggesting that for sources of similar luminosity, larger sources will typically have older spectral ages.

5.9.3 Lobe Expansion Speeds

The FRII objects in my sample, ILTJ112543 and ILTJ121847, have substantially slower growth rates than the FRI objects in the sample. The growth rates of the FRII galaxies are lower than those recently found by Ineson et al. (2017) who, using a representative sample of 37 FRII galaxies, found only two sources with an expansion speed below Mach 1, both of which were approximately 0.7. Whilst the sample of Ineson et al. is more luminous, and hence more powerful than mine, I note that in their study they found no relation between radio luminosity and advance speeds. It remains possible that the slow advance speeds of these two objects are related to the spiral nature of the hosts, however, these results continue to suggest that these hosts may have been misidentified and that the true source is at a higher redshift.

The majority of the sources studied by Parma et al. (1999) are FRIIs and have lobe advance speeds between 500 and 5000 km s$^{-1}$. The advance speeds of my FRI sources are
therefore similar to the slower sources in the Parma et al. sample. Previously observed GSJ have speeds between about Mach 3 and 5, which is again consistent with my results (Croston et al., 2007, 2009; Mingo et al., 2011, 2012).

Though, as noted earlier, my speed estimates should be considered as upper limits, it appears that the FRIs in the sample are capable of driving strong shocks ($M > 2$). It is possible that some of the zero-age emission seen in the lobes of some of these sources is caused by shock fronts re-accelerating plasma, though further observations are needed to confirm this.

The possibility of strong shocks means that the energy outputs estimated in Section 4.7, which assumed adiabatic expansion, should be considered as lower limits. Since Chapter 4 showed that GSJ lobes potentially contain enough energy to have a significant effect on the host, the impact of these low-luminosity sources upon the evolution of their hosts could be substantial.

5.10 Summary and Conclusions

Of the eight sources I considered to be GSJ based on the LoTSS DR2 images, the S-band VLA images have confirmed the hosts of four and rejected one. Of the remaining three, the hosts of two remain doubtful whilst one appears to be a remnant source. This clearly highlights the difficulty in identifying such small sources and emphasises the need for high angular resolution data to unequivocally identify GSJ.

For my sample of GSJ I find that:

- The existence of at least one galaxy-scale remnant shows that some sources never grow beyond the GSJ stage. The lobes of these sources will eventually transfer all of their energy into the host environment.

- GSJ have ages up to 60 Myr with the majority between 5 and 20 Myr. This is consistent with the evolutionary development of compact sources into larger radio galaxies.

- GSJ typically have lobe advance speeds a few times the local sound speed, with most predicted to be driving strong shocks into their surrounding environment.

- The energy stored in the lobes of GSJ is capable of having a significant effect upon the host’s evolution. My sources are therefore similar to those in the numerical simulations of (Mukherjee et al., 2016, 2018) who found low-power jets are capable of affecting the host’s ISM over large areas.

- The majority of my sources show little variation in spectral age, most likely dominated by the angular resolution of my images capturing different electron populations within a single beam, though physical mixing of electron population within the source cannot be ruled out.
• GSJ have an integrated spectral index similar to those of larger radio galaxies with no sign of a spectral turnover at frequencies above 150 MHz making them distinct from the GPS sources and meaning their turnover is at lower frequencies than all but the largest CSS sources.

• The existence of larger radio galaxies shows that some GSJ must evolve beyond this stage. The youngest, most luminous source in my sample, ILTJ145604, has some of the fastest expansion speeds and may be evolving into a larger, FRI/FRII-type source.

This work has highlighted the potential impact of young, low-luminosity sources upon galactic evolution. Future releases of LoTSS are expected to produce larger samples of GSJ that, coupled with high angular resolution, multi-wavelength data, will provide a better understanding of the full extent of the impact of these source on their hosts.

The GSJ sample discovered in Chapter 4 was not designed to specifically search for remnant GSJ. The presence of at least one galaxy-scale remnant within the VLA sample suggests that more will be observed by the LoTSS survey. Future releases of LoTSS should be used to find a larger selection of these interesting objects and determine their prevalence.
Chapter 6

Galaxy scale jets at X-ray frequencies

6.1 Introduction

In order to understand how feedback from radio jets is affecting the host, it is vital to understand the types of environment into which the jets are expanding. As discussed in Section 1.4 these regions are characterised as a hot thermal plasma emitting at X-ray frequencies via the bremsstrahlung process. As described in that Section, using X-ray observations it is possible to measure the mass, temperature, density and pressure of the environment.

X-ray observations can also be used to detect the presence of shocks caused by the expanding radio lobes. Shocks are described in Section 1.5 and can also be modelled to find the temperature, density and pressure within the shocked region. Using these measurements, it has been shown that the energy transferred in shocks can be over an order of magnitude more than the energy transferred via adiabatic expansion alone (e.g. Nusser et al., 2006; Croston et al., 2007).

The sources presented in Chapter 4 provide the first large catalogue of GSJ that can be used in X-ray studies to categorize the types of environment in which they reside and to search for evidence of shocks and how they are directly affecting the host. To perform an initial study, four of the GSJ selected for VLA follow up (Chapter 4.2) were also selected for X-ray follow-up. Whilst I estimated the internal lobe pressures of the sources (see below), the predictions for X-ray detectability needed for the proposal were done by my supervisor, J. Croston. The sources selected had to satisfy the following criteria:

- The source lobes are strongly over-pressured based on a comparison of estimated internal pressures (derived from equipartition estimates using the LoTSS DR1 data) and external environmental pressure (based on previous studies of similar galaxies).
- The source must be detectable at X-ray frequencies. The density of the shocked region was estimated based on the internal equipartition pressure and an assumed shock shell temperature of 1 keV. Based on the size of shocks seen in previous GSJ (Croston et al., 2007, 2009; Mingo et al., 2011, 2012) and the assumed shocked shell temperature, the estimated X-ray count rate was calculated.
They covered both FRI and FRII radio morphologies.

They covered both spiral and elliptical host types.

Using the above estimates, the shocks were predicted to have a low surface brightness so that XMM-Newton (XMM, described in Section 3.2.2), was selected for the observations due to its sensitivity to extended, low surface brightness emission. As a result, an additional requirement was imposed that the predicted width of the shocks were well matched to XMM’s PSF. Of the sources that satisfied the above criteria, the four with the highest predicted count rates and therefore the shortest observing times were submitted.

The four sources initially selected for X-ray follow-up were ILT J112543.06+553112.4, ILT J120645.20+484451.1, ILT J121847.41+520128.4 and ILT J145604.90+472712.1. A proposal for XMM observing time was submitted by J. Croston following which observation time was allocated for two of the sources, ILT J112543.06+553112.4 and ILT J120645.20+484451.1 (hereafter ILTJ112543 and ILTJ120645). Details of the sources observed are given in Table 6.1.

<table>
<thead>
<tr>
<th>Source Name</th>
<th>z</th>
<th>$N_H$ ($10^{20}$ cm$^{-2}$)</th>
<th>Scale (kpc/arcsec)</th>
<th>Total Length @ 3 GHz (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.00963</td>
<td>0.749</td>
<td>0.20</td>
<td>13</td>
</tr>
<tr>
<td>ILT J120645.20+484451.1</td>
<td>0.0646</td>
<td>2.11</td>
<td>1.25</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 6.1: Details of the sources observed with XMM. $N_H$ is the neutral hydrogen column density along the line of sight towards the sources according to the NASA website https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl.

For the remainder of this chapter, using the data from these observations, I aim to:

- Look for any spatial relation between X-ray and radio images.
- Search for evidence of shocks.
- Calculate the temperature and density of the environment into which the radio lobes are expanding.
- Calculate the energy density of non-radiating particles needed for pressure balance.

### 6.2 The Data

The XMM X-ray observations for ILTJ112543 and ILTJ120645 are available under observation IDs 0844260101 and 0844260201 respectively. ILTJ112543 was observed on 22nd October 2019 for just over 25 kiloseconds and ILTJ120645 was observed from the 13th to 14th November 2019 for just over 81 kiloseconds.

The data processing was done following the procedures described in Section 3.4. The data was initially filtered using the bitmasks 0x766a0600 for the MOS cameras and 0xfa000c for the pn camera. As described by Evans et al. (2008), these filters are similar to the standard #XMMEA_EM and #XMMEA_EP filters used to remove bad columns and
rows but also exclude events from outside the field of view. The pn data was also filtered to only include single and double events (PATTERN$\leq$4) and the MOS data was filtered using the standard pattern mask (PATTERN$\leq$12).

During the observation ILTJ112543 experienced negligible background flaring whilst ILTJ120645 experienced minor flaring. To allow accurate measurements of any low surface brightness regions, good time-interval (GTI) filtering was applied to both sources to remove background flares. As described in Section 3.4.1.2, this was done by constructing lightcurves at an energy range where the contribution from the AGN is expected to be negligible (10-12 keV for the MOS cameras and 12-14 keV for the pn camera) and identifying periods where the count rate was more than 20 per cent above the base rate. The lightcurve generated for ILTJ120645 can be seen in Figure 3.9, where time periods with a count rate above 100 were cut. The data was then corrected for vignetting. The standard function `epatplot` detected no problems with pileup.

For the pn-camera, 6.3 per cent of detected counts are recorded with the incorrect y-coordinate. These out-of-time (OOT) events are caused by photons striking the detector during read-out. These events cause an additional positional-dependent background component that can affect analysis of low-surface brightness regions. To account for this the standard task, `epchain` was used to generate an OOT events list for the pn-camera which was scaled and subtracted as a background component. The resulting events files were used in the following chapters to perform all the X-ray data analysis and image generation presented.

Throughout this chapter, when comparing the X-ray images produced with radio images of the same source, I use S-band (2-4 GHz) radio data obtained using the Karl G. Jansky Very Large Array (VLA). Details of these radio observations and data reduction is given in Section 5.3.

6.3 X-ray Analysis

In this section I present the results of the X-ray analysis for the two sources. I firstly describe how visual images were constructed for the two sources before describing the results for each source separately.

6.3.1 Images

As described in Section 3.4.2, separate images were produced for the MOS and pn cameras. Before combining into a single image the two MOS images were weighted by a factor to account for the difference in sensitivity compared to the pn camera. Separate exposure maps were generated for each camera which were then summed to create a combined exposure map. This combined map was then used to exposure correct the combined image. In order to search for structures visible at different energies, images were produced using several different ranges (0.5-5 keV, 0.5-2 keV and 2-4 keV). To search for structures visible
at different scales each of these images was also smoothed using a 3, 5 and 10 arcsecond Gaussian kernel.

Figure 6.1 shows images for both sources in the 0.5-5 keV range smoothed with a 5 arcsecond Gaussian kernel. Both images are overlaid with the radio contours seen by the VLA at 3 GHz with the minimum contour set to 3 times the RMS radio noise.

As can be seen in Figure 6.1, XMM did not detect any strong emission from ILTJ112543. The small patches that can be seen for this source are consistent with background emission. For ILTJ120645, XMM detected a roughly circular region of emission centred on the core of the radio galaxy. The appearance of this emission is consistent with being from the hot gas environment surrounding the source, extending out to a radius of approximately 50 arcsec (60 kpc) before becoming indistinguishable from the background. None of the images produced show obvious features indicating the presence of shocks and none of them showed any difference in structure across either the different energy ranges or spatial scales tested. There is no correlation between the radio lobe morphology and any visible structures in the X-ray observations.

6.3.2 ILT J112543.06+553112.4

As mentioned in Section 6.3.1, there is no obvious visible X-ray emission detected for this source. To quantify if there is any significant emission I used the 10 kpc circular region centred on the optical host shown in Figure 6.1 and compared it with an off-source region of the same size (not shown). This region was used as it is large enough to encompass all of the radio emission observed by the VLA. Using the 0.5-5.0 keV energy range, the total counts in the background are $432 \pm 21$ and in the source region are $476 \pm 22$. The difference in total counts between the two regions is therefore $1.5\sigma$, consistent with there being no observable emission from the host.

After performing background subtraction, this low level of counts makes it impossible to fit a spectrum for this source. Instead, it was only possible to calculate upper limits for the environmental luminosity. This was done by assuming a temperature and, after allowing for Galactic $N_H$ absorption, adjusting the normalisation of an apec model to give a count rate that is three times the uncertainty observed in the source region shown in Figure 6.1. The unabsorbed luminosity was then obtained from the model using xspec’s lumin function.

The apec model used in this analysis also requires a metallicity to be input. Using XMM to study a range of galaxy groups and clusters, Lovisari & Reiprich (2019) found the metallicity profiles for groups hosting an AGN ranged from about 0.8 close to the core out to about 0.3 near the group edges. They also found the profiles decreased rapidly from the centre until about 0.2 - 0.3$R_{500}$ where they flatten and stay roughly constant. Using the $R-T$ relation of Arnaud et al. (2005), the 0.2$R_{500}$ distances corresponding to temperatures of $kT = 0.1$ and 1.5 keV, values that are marginally broader than those typically associated with galaxies in sparse group environments (Lakhchaura et al., 2018; Mulchaey, 2000), are 35 and 160 kpc respectively. Even the smaller distance is greater than the maximum...
Figure 6.1: Heat map shows 0.5 - 5 keV XMM images smoothed with a 5 arcsec Gaussian kernel overlaid with 3 GHz VLA radio contours in yellow. Shown are ILTJ112543 (top) and ILTJ120645 (bottom). The green circle on ILTJ112543 shows the region used in the spectral analysis to calculate an upper limit for the temperature. The blue circles show the regions used to try and identify the correct host, solid centred on the optical host and dashed located midway between the hotspots.
Chapter 6. Galaxy scale jets at X-ray frequencies

Figure 6.2: Upper limits for the environmental luminosity of ILTJ112543 as a function of temperature.

extent of 10 kpc that I am considering. Equally, the majority of the environment I am considering lies outside the galaxy core and so I used an intermediate metallicity of 0.5 when calculating the maximum possible environmental luminosity, though I note that the results do not depend strongly on this choice. The upper limit for the unabsorbed luminosity was then calculated for temperatures between \( kT = 0.1 \) and \( 1.5 \) keV.

The results of this analysis are shown in Figure 6.2 and whilst the true value is somewhere below this curve it is not expected to be significantly below as spirals are typically found to have X-ray luminosities around \( 10^{38} - 10^{40} \) erg s\(^{-1}\) (Li et al., 2011; Li & Wang, 2013). For ILTJ112543, luminosities above \( 10^{39} \) erg s\(^{-1}\) are only possible under very limited conditions where the environmental temperature is below about \( kT = 0.4 \) keV. This value is toward the lower end of the observed range of \( kT = 0.3 - 2.0 \) keV typically found across the whole range of galaxy groups (Mulchaey, 2000) and is therefore unlikely so that a luminosity of around \( 10^{39} \) erg s\(^{-1}\) or below is expected.

As discussed in previous chapters (see Sections 4.3.1, 5.4.1, 5.7.2 and 5.9.3), it is possible that the host identified in the LoTSS value added catalogue is wrong and the true host is an unobserved background galaxy. In particular, it can be seen in Figure 4.7 that there is a small island of radio emission located to the south east of the optically identified host midway between the hotspots. As described in Section 4.3.1, this emission may be due to some feature within the jet itself or it may be emanating from the core of the true, unseen, host.

In order to try and determine whether the true host is either the current optically
identified host or an unseen galaxy located within the island of emission to the south east, I tried to fit a spectrum to both regions shown in Figure 6.1, to see if either had a power law profile typically associated with AGN hosts (e.g. Reeves & Turner, 2000; Ishibashi & Courvoisier, 2010). Both of the regions tested have a diameter of 15.1 arcsec, the size of the half equivalent width (HEW) of the pn camera\(^1\). The regions around the optical host and the island of emission have 9 and 6 counts respectively before background subtraction. Using an identically sized background region (not shown) the total counts were found to be 13±4 so that both regions have a background-subtracted number of counts consistent with zero. Even ignoring background subtraction, neither region has sufficient X-ray counts to perform a spectral analysis and so the current X-ray data cannot confirm the true host.

6.3.3 ILT J120645.20+484451.1

In order to quantify the temperature, pressure and density of the hot gas environment surrounding ILTJ120645, I performed a spectral analysis of the data using the methods described in Section 3.4.3. Based on a visual inspection of the image, this analysis was done using a circular region of 50 arcsecond radius centred on the coordinates of the host galaxy and excluding the two background sources shown in Figure 6.3. After grouping the observed data into groups each containing at least 20 counts after background subtraction, spectra were generated jointly for all three cameras using standard background subtraction techniques.

The extended emission shown in Figure 6.1 is circularly symmetric and has the appearance of a hot-gas environment. Therefore, in order to confirm a thermal source and to find its temperature, I fitted an \textit{apec} model combined with a \textit{phabs} component to allow for Galactic \(N_H\) absorption in the direction of the target (model components are described in Section 3.4.3.7). Separately, I also fitted a \textit{phabs(apec + power law)} model to the data in order to assess the impact of any component from the central AGN. In each case the normalizations were allowed to vary and for the \textit{apec} model, the metallicity abundance and temperature were allowed to vary. For the model including a power law, the index was allowed to vary. The results of the model fitting are given in Table 6.2. The spectrum for each of the three cameras using the \textit{phabs(apec)} model is shown in Figure 6.4.

As can be seen, the \textit{apec} model had a reduced chi-squared of 0.98 for 127 degrees of freedom and the \textit{apec + power law} model had a reduced chi-squared of 0.95 for 123 degrees of freedom. Whilst the difference in the reduced chi-squared is marginal, both the abundance and the power law index for the \textit{apec + power law} are poorly constrained so that the \textit{apec} model better represents the data. This is reinforced by the power law component in the \textit{apec + power law} model only contributing 14 per cent of the total flux density, again suggesting a minor contribution from the central AGN.

To assess any variation in the environmental temperature with radius I performed three spectral fits, one for the inner region represented by a circle of 10 arcsec (\(\sim 13\) kpc) radius, a second for the outer region using an annulus with inner and outer radii of 25

\(^1\)https://www.mssl.ucl.ac.uk/www_xmm/ukos/onlines/uhb/XMM_UHB/node16.html
**Figure 6.3**: Colour map shows the X-ray environment of ILTJ120645. The outermost green annulus is the background region, everything within the innermost green circle was used in the spectral analysis. Blue circles show the annuli subdivisions used for the surface brightness and pressure profile analysis. White circles show the background sources. Yellow contours show the radio jets as observed at 3 GHz.

### Table 6.2

<table>
<thead>
<tr>
<th>Model</th>
<th>$kT$ (keV)</th>
<th>Abundance $(Z_\odot)$</th>
<th>$\Gamma$</th>
<th>Reduced $\chi^2$</th>
<th>Degrees of Freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>$apec^*$</td>
<td>1.06 ± 0.01</td>
<td>0.52 ± 0.08</td>
<td>0.98</td>
<td>0.98</td>
<td>127</td>
</tr>
<tr>
<td>$apec + po$</td>
<td>1.05 ± 0.01</td>
<td>1.24 ± 5.76</td>
<td>1.7 ± 1.4</td>
<td>0.95</td>
<td>123</td>
</tr>
</tbody>
</table>

*Results of this model are used throughout this chapter.*
and 50 arcsec (∼ 30 and 60 kpc) and a third for the region in between. All regions were centred on the optical host and were chosen so that after grouping there were about 20 groups in each, allowing a good spectral fit. The outer and middle regions both gave a temperature of $kT = 1.05 \pm 0.03$ keV which is only slightly less than the value of $1.08 \pm 0.02$ keV found for the inner region. Whilst the temperature is expected to drop at larger radii the small variation seen means it is reasonable to characterise the entire region as a single temperature. These values are typical of those found in sparse/group environments. Lakhchaura et al. (2018) studied the environments of 49 galaxies in group environments finding temperatures ranging between 0.2 - 1.6 keV with values above 1 keV being rare. My values, whilst not atypical, are therefore towards the upper end of the range of values expected.

As described in Section 3.4.3.6, vignetting means that a lower percentage of X-ray photons are detected towards the edge of the field of view compared to the centre. However, vignetting does not affect the particle background. To account for any effects this has upon the spectra I also derived spectra using the double background subtraction techniques described in Section 3.4.3.6. Adopting this technique for the 50 arcsecond region used above resulted in a reduced chi-squared fit of 0.82 for 158 degrees of freedom with the $\text{phabs(apec)}$ model and gave $kT = 1.06 \pm 0.01$ keV and an abundance of $0.54 \pm 0.08$ solar. As expected, since ILTJ120645 is relatively small and is at the centre of the observation, these results are almost identical to those found using single subtraction techniques. These results confirm that spatial variations are not significant when generating spectra for this source. Therefore, throughout the rest of this chapter I only consider the results of the $\text{phabs(apec)}$ model (shown in Table 6.2) derived using the simpler, ordinary background subtraction techniques.

### 6.3.3.1 Spatial Profiles

In order to compare the pressure within the radio lobes with those of the surrounding environment (see Section 6.4) it is necessary to generate a pressure profile for the environment. Similarly, in order to assess the potential existence of any strong shocks (see Section 6.5) it is also necessary to generate a density profile for the environment. I therefore firstly derive a surface brightness profile which I then use to derive both pressure and density profiles as well as the environmental luminosity.

The surface brightness profile for ILTJ120645 was generated using the methods described in Section 3.4.4. This was done by subdividing the same 50 arcsec radius region around the host galaxy as was used to generate the spectra in Section 6.3.3 into a series of annuli, each with a 5 arcsec difference between the inner and outer radii. Since the count rate is higher towards the centre, the innermost 5 arcsec was subdivided further into a 1.5 arcsec circle and a 1.5 - 5 arcsec annulus so as to provide a higher angular resolution profile around the core. The same background sources identified in Section 6.3.3 and shown in Figure 6.3 were excluded resulting in eleven separate regions being used for the surface brightness analysis, with a minimum number of 50 counts within each region.
Chapter 6. Galaxy scale jets at X-ray frequencies

Figure 6.4: The X-ray spectrum of ILTJ120645 fitted using a \textit{phabs(apec)} model. Green represents the pn camera, black is MOS1 and red is MOS2. Top half: the crosses show the normalised number of counts in each energy bin and the solid lines show the model fits. Bottom half: the residuals after subtracting the model from the data.

For the background region an additional annulus was used with the same centre as the other annuli but with inner and outer radii of 50 and 60 arcsec respectively. The location of these regions is shown in Figure 6.3 as a series of green circles. The surface brightness profile, found by dividing the number of counts observed by the area of each region, is shown in Figure 6.5.

A model was then fitted to the surface brightness profile using a Markov Chain Monte Carlo (MCMC) method as described in Section 3.4.4.2. Priors were found by carrying out an initial MCMC fit using extremely wide parameter ranges and using the results to find a suitable range of prior values. Both the maximum likelihood and Bayesian estimates for the beta model fitted are given in Table 6.3. As can be seen the maximum likelihood and Bayesian values are very close, I therefore use the maximum likelihood values throughout the rest of this chapter.

Both the maximum likelihood model and the observed data points are shown in Figure 6.5. As can be seen the surface brightness profile is well-described using a single beta model up to a radius of about 30 arcsec after which the model has a slightly lower surface brightness than observed. This trend remains even if the outermost 4 points shown are combined into two separate groups. It is currently unclear what the cause of this discrepancy between the data and the model is, however when studying the particle content (Section 6.4) and the possibility of shocks (Section 6.5) I use the high angular resolution VLA data where each lobe has a maximum extent of under 20 arcsec at which distance the model is a good representation of the data. Therefore, the results of this chapter are
Figure 6.5: Surface brightness profile for the environment of ILTJ120645. The data points are shown in blue and the beta model using the maximum likelihood parameters is shown in black.
Using the results for the maximum likelihood model, the X-ray luminosity of the source out to \( R_{500} \) was calculated. Using the \( R-T \) relation described in Table 2 of Arnaud et al. (2005), the value of \( R_{500} \) for this source is 509 arcsec (640 kpc). Using Equation 5 of Birkinshaw & Worrall (1993) which relates the beta model parameters to the surface brightness and integrating out to the \( R_{500} \) radius, I find a count rate of \( 6.85 \times 10^{-3} \) counts s\(^{-1}\). Using xspec to create an apec model that produces the same number of counts within the 0.5 - 5.0 keV range and then using that model to calculate the bolometric flux density and luminosity gives \( S_{X,R_{500}} = 3.3 \pm 0.1 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) (3.3 \( \pm 0.1 \times 10^{-17} \) W m\(^{-2}\)) and \( L_{X,R_{500}} = 3.4 \pm 0.1 \times 10^{44} \) erg s\(^{-1}\) (3.4 \( \pm 0.1 \times 10^{34} \) W). This result is at the least luminous end of the range of values typically associated with the environments of radio loud galaxies (Worrall & Birkinshaw, 2000; Croston et al., 2008a; Ineson et al., 2015).

Lakhchaura et al. (2018) also studied the environments of 49 galaxies, most of which are in a similar sparse environment to my GSJ. They report luminosities within 10 kpc of the host in the 0.5-7 keV range. Therefore, in order to compare with their results I also calculated the luminosity within 10 kpc of the optical host using the same energy range finding \( L_{X,10kpc}(0.5 - 7 \text{ keV}) = 8.0 \times 10^{40} \) erg s\(^{-1}\) (8.0 \( \times 10^{33} \)) once again, my results are at the least luminous end of the range of values typically observed. However, despite the low luminosity it is still consistent with the \( L_{X-T} \) relation (Croston et al., 2005a; Bharadwaj et al., 2015). Using optical data from DR14 of the Sloan Digital Sky Survey (Abolfathi et al., 2018) and applying the criteria of Buttiglione et al. (2010), ILTJ120645 is classified as a LERG and is also consistent with the (tentative) relation found by Ineson et al. (2015) for LERGs between their radio luminosity and the X-ray environment.

As described in Section 3.4.4, the X-ray bremsstrahlung emissivity, and hence surface brightness, depends upon the density of the emitting plasma. Therefore, using the results of the MCMC code the density profile given in the top panel of Figure 6.6 was derived. Further, since density and pressure are related via the ideal gas law, using a constant environmental temperature of 1.06 keV (Section 6.3.3) the pressure profile shown in the bottom panel of Figure 6.6 was also derived.

The observed pressures are similar to those found for other radio galaxies (e.g. Worrall & Birkinshaw, 2000; Croston et al., 2008a, 2018). In order to compare densities with Ineson et al. (2015), who use a population of 55 radio galaxies to calculate the ICM electron density at a radius of 0.1\( R_{500} \), I firstly calculate the proton number density at the same radius.

### Table 6.3: Results of the MCMC model fit

<table>
<thead>
<tr>
<th>Method</th>
<th>( \beta )</th>
<th>( r_{\text{core}} )</th>
<th>( \beta_{\text{norm}} )</th>
<th>( PSF_{\text{norm}} )</th>
<th>( \chi^2 ) (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Likelihood</td>
<td>0.49</td>
<td>0.64</td>
<td>( 2.3 \times 10^{-4} )</td>
<td>( 1.93 \times 10^{-4} )</td>
<td>8.48 (8)</td>
</tr>
<tr>
<td>Bayesian Estimate</td>
<td>0.50( ^{+0.20}_{-0.12} )</td>
<td>0.63( ^{+0.46}_{-0.43} )</td>
<td>( 2.46 \times 10^{-4} )</td>
<td>( 2.78 \times 10^{-3} )</td>
<td>12.45 (8)</td>
</tr>
</tbody>
</table>

\( \beta \) is the beta parameter, \( r_{\text{core}} \) is the core radius in arcseconds, \( \beta_{\text{norm}} \) and \( PSF_{\text{norm}} \) are the beta and PSF normalisations, both in electron density per m\(^3\).

unaspected by this discrepancy.
For ILTJ120645 this equates to a distance of 51 arcsec (64 kpc) and is therefore at the very edge of the range of measured values where the proton number density is $284^{+39}_{-27}$ particles per cubic metre. Using the relation $n_e = 1.2n_p$ (Kaastra et al., 2008) this equates to an electron density of $335^{+46}_{-33}$ particles per cubic metre which is at the lower end of the range of values found by Ineson et al. This is the primary cause of the low observed luminosity.

### 6.4 Particle Content

In this section I investigate the pressure ratio between the radio lobes and the external environment of ILTJ120645 before using this result to estimate the contribution of non-radiating particles to the total energy budget of the radio lobes.

When measured at the mid-point of the lobe, the pressure ratio is expected to be at least unity, otherwise the lobe is contracting. Whilst this may be the case for individual sources it cannot be the case for the majority. Despite this many FRIs are observed to have underpressured lobes when measured under equipartition conditions, assuming no non-radiating particles (e.g. Croston et al., 2003, 2008a; Croston & Hardcastle, 2014; Croston et al., 2018). This pressure deficit can either be accounted for by stronger magnetic fields, entrainment of a significant population of non-radiating particles, or a mixture of the two. The currently favoured model is that entrainment accounts for the majority of the pressure deficit.

To investigate the pressure ratio for ILTJ120645, I used the pressure profile for the external environment, shown in the bottom panel of Figure 6.6 to estimate the external pressure at the lobe midpoint. Using the 3 GHz VLA data (shown in Figure 6.3) the midpoints of both the West and East lobes were found to be at approximately 6 arcsec from the core. According to the pressure profile, the external pressure at the midpoint is expected to be $1.84^{+0.14}_{-0.06} \times 10^{-12}$ Pascals.

To estimate the internal pressure, I used the 150 MHz - 3 GHz spectral index of $\alpha_{150\text{GHz}}^{3\text{GHz}} = 0.8 \pm 0.1$ found in Section 5.5 which corresponds to an injection index of $2.6 \pm 0.2$ (Equation 1.12). As described in Section 1.3, the injection index represents the power-law energy distribution of the radio-emitting electrons. As shown in Figure 5.4, there is no indication of a spectral turnover and the spectral profile can be described using a simple power law model without a break frequency.

The internal pressure within the lobes was estimated using the PySYNCH code, first used in Hardcastle et al. (1998), under equipartition energy conditions. Assuming no non-radiating particles and using minimum and maximum electron energies of $\gamma_{\text{min}} = 10$ and $\gamma_{\text{max}} = 10^6$ along with the injection index calculated above, the internal pressure of the lobes is $3.46 \times 10^{-13}$ Pascals, approximately an order of magnitude less than the external pressure. The magnetic field strength under these conditions is 1.0 nT.

In order to assess the contribution of non-radiating particles within the lobes I repeated the above calculation allowing the $K$ number to vary until the internal pressure matched the external where $K$ is defined as the sum of the electron and proton energy densities.
Figure 6.6: Density (top) and pressure (bottom) profiles for the environment of ILTJ120645. The coloured region represents the 1σ uncertainty.
divided by the electron energy density. Performing this calculation gives $K = 90^{+60}_{-35}$ with a corresponding magnetic field strength of $3.7^{+0.2}_{-0.1}$ nT.

The $K$ value for ILTJ120645 is similar to what has been previously found for the population of FRI radio galaxies. Whilst noting that the range of values found for $K$ varies significantly (e.g. Dunn & Fabian, 2004; Birzan et al., 2008; Croston et al., 2008a) with maximum values typically of the order of a few hundred, Croston et al. (2018) found that a value of $K = 10$ was typically required in order for FRIs to achieve pressure balance assuming equipartition magnetic fields. Whilst ILTJ120645 is therefore higher than the average, it is significantly less than the value of $K = 200$ found for NGC 3801, the only other GSJ whose particle content has previously been measured. These values therefore suggest that the radio lobes of GSJ may contain a substantial amount of non-radiating particles, possibly entrained from the host environment.

The above results are based on the assumption of pressure balance between the radio lobes and the surrounding environment. In order for the lobes to be overpressured with respect to the environment, even more extreme values of $K$ are required. For example, in order for the internal lobe pressure to be twice that of the surrounding environment values of $K = 344^{+237}_{-128}$ are required. This is similar to the value found for NGC 3801 so that it is possible the lobes of ILTJ120645 are mildly overpressured. This means that, whilst the possibility of strong shocks (discussed in the following section) cannot be ruled out they are unlikely and, contrary to what was concluded in Section 5.10, this source is more likely to be producing weak shocks.

### 6.5 Shocks

In order to further investigate whether ILTJ120645 could be driving either a strong or weak shock that cannot be detected over the environmental emission I firstly see if there are any localised X-ray surface brightness enhancements that could be attributed to the presence of unobserved shocks. Secondly, I estimate the maximum possible shock strength for any underlying shocked regions.

To investigate both of these questions, I defined two half-spherical shells at the western and eastern tips of the radio emission to represent the regions where shocks are most likely to form. The inner radii of both shells were 3 arcsec, just large enough to enclose the 3 GHz radio emission. Previous observations of the shocked gas shell (i.e. the region between the shock front and the radio lobes) have shown depths ranging from a few hundred parsec (Croston et al., 2009; Jetha et al., 2008) up to several kpc (e.g. Fabian et al., 2003). Since gas accumulates in this region over time, the young age and low power of ILTJ120645 suggest that the shell thickness is likely to be towards the lower end of this range. I therefore initially follow Croston et al. (2007) and estimate the shell thickness as being 200 pc, though I return to this assumption in Section 6.5.2. The size and location of these assumed shock regions are shown in Figure 6.7.
Cross-sections of the two assumed shock regions are shown at either end of the 3GHz radio emission (yellow contours). The western shock region is shown in blue and the eastern in green. The two solid lines show the assumed 200 pc thick shocked region. Also shown is the cyan cross representing the centre of the X-ray emission and the two semi-circular, local background regions located immediately above the source.
6.5. Shocks

<table>
<thead>
<tr>
<th>Location</th>
<th>Shocked Region</th>
<th>Non-shocked Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Shock</td>
<td>39 ± 6</td>
<td>23 ± 5</td>
</tr>
<tr>
<td>Eastern Shock</td>
<td>31 ± 6</td>
<td>29 ± 5</td>
</tr>
<tr>
<td>Total</td>
<td>70 ± 8</td>
<td>52 ± 7</td>
</tr>
</tbody>
</table>

Table 6.4: Background subtracted counts for hypothetical shocked regions vs non-shocked regions.

6.5.1 Evidence of Existing Shocks

In order to test the possibility that some of the observed X-ray emission is due to an underlying shocked shell, I compare the total X-ray counts in the 0.5 - 5.0 keV range from the shocked region with a local region of the same area where shocks are not expected to be present. Assuming the environmental emission is spherically symmetric, the local (unshocked) region used was found by rotating the emitting region around the centre of the X-ray emission so that it lies approximately perpendicular to the jet direction (shown in Figure 6.7).

In order to get a reliable estimate of the background level, an estimate was obtained using another region of the same size that was located at a radial distance of 1′ from the X-ray centre (not shown). The background level was subtracted separately for each of the XMM cameras from both the emitting and local background regions to get the background subtracted count rates. In order to improve the count statistics, the results from each of the three cameras were combined as were the two shocked regions. Poisson statistics were used to calculate the errors. For reference, Table 6.4 gives the results for both the western and eastern regions separately as well as the overall total.

As can be seen from the combined totals, there is no significant excess in the total number of photons seen in the assumed shocked regions, with the excess being around 1.6σ. I note that whilst in practice the XMM PSF means that any photons emitted would be detected over a larger area than just the emitting regions used above, increasing the size of the areas by the HEW does not qualitatively alter this result with any shocks that are present remaining undetected.

6.5.2 Possibility of Unobserved Shocks

In order to assess whether there may be an unobserved shock (strong or weak), it is necessary to estimate the number of X-ray counts for an assumed set of shock conditions and compare this with observations to see if the hypothetical shock would produce a number of counts greater than three times the observed background noise. To estimate the number of counts emitted by a strong shock that could be produced by the lobes of ILTJ120645 within the measured environment, I first estimated the volume, gas density and temperature of the shock. Apart from adjusting the thickness of the shocked region (as described below), I use the same emitting regions as described in Section 6.5.1 from which I obtain the shock volume.
In the case of a strong shock, the temperature of the shocked gas is related to both the temperature of the unshocked material and the Mach number of the shock according to the formula (Longair, 2011):

$$\frac{T_{\text{shell}}}{T_{\text{ISM}}} = \frac{2\gamma_{\text{ad}}(\gamma_{\text{ad}} - 1)M^2}{(\gamma_{\text{ad}} + 1)^2}$$

where $\gamma_{\text{ad}}$ is the adiabatic index of the gas which for a monatomic gas is $\frac{5}{3}$. The expansion speeds of the west and east lobes of ILTJ120645 were estimated in Section 5.8 as Mach $3.4^{+0.6}_{-0.7}$ and $4.5^{+0.3}_{-1.4}$ respectively. This leads to predicted shocked gas temperatures of $kT = 3.8^{+1.5}_{-1.4}$ and $6.7^{+0.9}_{-3.5}$ keV respectively. The temperature for a weak shock will be lower; however, the emissivity of the shocked gas depends only weakly on temperature and so this temperature is used throughout the remainder of this section.

Using the density profile of the environment, shown in the top panel of Figure 6.6, the environmental electron number density at the tip of the radio lobes is about $2350 \pm 150$ electrons per cubic metre (equivalent to a proton number density of $2000 \pm 100$). Any strong shocks would have a density enhancement of four whilst weak shocks would have a density somewhere between one and four. Using these estimates for the density, temperature and volume of a strong shock, an apec model was used to predict the hypothetical count rates for the corresponding shock.

These hypothetical count rates were then compared with observations of the region over which the assumed shock would be observed. However, since the estimated size of the emitting region is far smaller than the XMM PSF any photons generated by a shock front would be observed over a larger surface area than is occupied by the shock. The half energy width (HEW) is the diameter over which half of the energy from a point source would be detected and for MOS1, MOS2 and pn are $13.6$, $12.8$ and $15.1$ arcsec$^2$. I therefore increased the hypothetical shock regions by these amounts to find the apparent region size over which half of the photons emitted by the shock would be observed. I then found the observed uncertainty in the count rates for these regions in the $0.5 - 5.0$ keV range.

Since only half of the photons emitted by the assumed shock would be observed over the region tested, I compared half the hypothetical count rates with the observed count rate uncertainty. If the hypothetical count rate was less than three times the observed uncertainty, then it is possible for the assumed shock to be present and remain unobserved. Repeating this analysis using several assumed volumes, it was found that there could be an unobserved strongly shocked gas region up to about $5$ kpc in thickness. As described above, this is far larger than the shell thickness anticipated for a radio galaxy of this power and age and so strong shocks cannot be ruled out for the most plausible shocked shell thicknesses. Further, since strong shocks cannot be ruled out, it is also possible that this source is driving unobserved weak shocks into its environment.

\[\text{https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/onaxisxraypsf.html}\]
6.6 Discussion

No shocks are detected for either ILTJ112543 or ILTJ120645. For ILTJ112543, this source is an FRII where X-ray emission from either shocks or from the hotspots is expected. The lack of any observed emission once again suggests that the host has been misidentified and that the true host may be a background galaxy at higher redshifts (see Sections 4.3.1, 5.4.1, 5.7.2 and 5.9.3). For ILTJ120645 the environmental luminosity (whilst not atypical) is towards the lower end of the range of values expected for a sparse, group environment and could be hiding the presence of shocks. However, the large proton content required to achieve pressure balance with the surrounding environment suggest that this source is likely expanding slowly and is therefore unlikely to be driving large scale strong shocks with weak shocks being considered more likely.

Similar to ILTJ120645, multiple studies have found that the lobes of FRI galaxies are typically underpressured compared to their environment (e.g. Morganti et al., 1988; Worrall & Birkinshaw, 2000; Dunn et al., 2005; Croston et al., 2018). Using a representative sample of FRI-type radio galaxies, Croston et al. (2008a) found internal lobe pressures ranging from about 70 times less up to being roughly in balance with the local environment. In comparison, ILTJ120645 is underpressured by approximately an order of magnitude, less than has been seen for many other sources. However, this is still significantly different to previous studies of two sources that could be considered as GSJ, NGC 3801 (Croston et al., 2007) and Cen A (Croston et al., 2009). Both sources revealed internal pressures greater than the surrounding environment under equipartition conditions. ILTJ120645 is therefore different to these GSJ, being more similar to the general population of FRI radio galaxies. Studies incorporating larger number of GSJ are therefore needed to discover whether the wider population of GSJ are generally over or underpressured.

In Section 5.8 I found supersonic advance speeds for ILTJ120645 of Mach $3.4^{+0.6}_{-0.7}$ and $4.5^{+0.3}_{1.4}$ for the west and east lobes. Noting that these speeds are upper limits, my pressure estimates do suggest that this source is likely to be expanding at substantially lower speeds. This may be partly due to underestimating the local sound speed. In Section 5.8 I assumed a local sound speed of around 400 km s$^{-1}$ based on an environmental temperature of $kT = 0.6$ keV but a more accurate sound speed would be 550 km s$^{-1}$ based on the measured environmental temperature of $kT = 1.06$ keV. Using this value, the lobe advance speeds become Mach $2.5^{+0.4}_{-0.6}$ and $3.2^{+0.3}_{1.0}$ for the west and east lobes respectively.

However, even these speeds seem unlikely and so it is also possible that the assumption used, that the oldest observed plasma seen was emitted when the jet first became active, is wrong. If the oldest observed plasma was in fact emitted when the lobes were already a sizeable proportion of their current size, then this would have a significant effect upon my speed estimates. It is also possible that the lobe advance speeds have changed over time and that the lobes were initially significantly overpressured, advancing faster than is seen at present. This would affect the estimates in Section 5.8 which are an average over the source lifetime. This also emphasises the need for further high angular resolution
observations so that more accurate speed estimation methods such as those of Alexander & Leahy (1987) can be applied and speed gradients calculated.

Whilst larger samples of GSJ need to be studied at X-ray wavelengths, the values of \( K = 90 \) for ILTJ120645, and \( K = 200 \) for another GSJ, NGC 3801 (Heesen et al., 2014), suggests that a high proton content may be common amongst this class of object. This supports the arguments of Dunn et al. (2005), that low power jets are likely to have higher rates of entrainment. For GSJ, the low power and large surface area of the lobes that is in direct contact with the relatively dense host environment, could therefore be responsible for entraining large numbers of protons from the environment. This is supported by simulations which also show that the jets of low power radio galaxies are more likely to mix with the environment (Mukherjee et al., 2020; Rossi et al., 2020; Massaglia et al., 2016).

6.7 Summary and Conclusions

Using \textit{XMM} observations of two GSJ, ILTJ112543 and ILTJ120645, no detection was found for the former whilst only the environment was observed in the latter. Analysing these data, it has been found that

- No shocks are observed in either source

- The upper limit for the luminosity of ILTJ112543 is expected to be about \( 10^{39} \) erg s\(^{-1}\), with higher luminosities unlikely. This is typical of the environments of spiral galaxies.

- For ILTJ120645, the bolometric luminosity is \( 3.4 \pm 0.1 \times 10^{41} \) erg s\(^{-1}\) and the temperature is \( kT = 1.06 \) keV. Whilst the luminosity is low and the temperature high for a source in a group environment, neither value is unusual.

- There is no observable spatial interaction between the radio lobes and the X-ray environment

- Existing X-ray observations cannot confirm the host of ILTJ112543 though the lack of any detection mean it is likely that the true host is an unseen background source.

- Similar to other FRI sources, the lobes of ILTJ120645 are under pressured compared to the environment with a proton content of \( K = 90^{+60}_{-35} \) and a magnetic field strength of \( 3.7^{+0.2}_{-0.1} \) nT required to achieve pressure balance.

- For ILTJ120645 strong shocks cannot be ruled out though the high proton content required to achieve pressure balance implies that weak shocks are more likely.

This work provides the first insights into the sorts of environments that GSJ inhabit, showing that they cover a wider range of temperature and luminosity than previously thought. The high proton content also suggests that the low power and the large surface
area of the lobes that are in direct contact with the host ISM mean entrainment may be a significant factor in understanding the energetics of GSJ.

Future X-ray studies are needed to obtain a larger, more representative, sample of the environmental conditions in which GSJ are to be found. Future studies are also needed to detect the presence of shocks that most GSJ are expected to be driving so that the impact this class of source has upon the immediate environment can be measured.
Chapter 7

Conclusions and further work

As described in Section 2.6, the aim of this work was to look at the potential role of feedback in radio galaxies producing physically small radio jets where the size of the jets means they are either directly interacting with the host’s interstellar medium or have recently done so. Throughout this thesis these jets are referred to as galaxy scale jets (GSJ). In order to study the potential role of feedback in GSJ I used LoTSS DR1 to identify a total sample of 195 sources. Using these sources, I then conducted the following investigations:

- to confirm the host identifications
- to investigate the properties of those galaxies hosting GSJ;
- to investigate the environments of GSJ;
- to investigate the spectral ages of a sub-sample of GSJ;
- to investigate the lobe expansion speeds of a sub-sample of GSJ and their potential for driving shocks into their environment;
- to investigate the potential for energetic feedback from GSJ to influence the evolution of the host galaxy.

As part of these investigations I used legacy surveys to identify the host and environmental properties of GSJ. I also reduced and analysed radio data for nine of my GSJs taken with the Karl G. Jansky Very Large Array plus X-ray data for two of my sources taken with the XMM-Newton telescope.

In this chapter I review each of the above areas giving a brief overview of what has been found during my research before discussing some future work that could be conducted to further enhance our understanding of galaxy scale jets.

7.1 Confirming the Host Galaxies

As stated in Section 5.1, the low frequencies used by LOFAR mean that any core radio emission from the AGN is less prominent. Combined with the 6 arcsec angular resolution of LOFAR this means that some of the optical host galaxies may have been misidentified in the LoTSS DR1 value added catalogue. Therefore, in order to try and confirm the host
identifications, a sample of nine GSJ that were representative of the wider population were chosen for high angular resolution follow-up using the VLA.

For one of the sources in this sample, the improved image processing techniques used for LoTSS DR2 suggested that this was not a genuine GSJ. I subsequently confirmed this using my VLA data. For the other eight sources, six were hosted by elliptical galaxies and two by spiral galaxies. My analysis of the VLA data showed that one of the elliptical galaxies was misidentified and, though not definitive, cast doubt on both the spiral galaxies (Section 5.4). One of these spiral galaxies was also studied in Chapter 6 though no detectable X-ray emission was observed preventing confirmation of the true host.

My results therefore show the difficulties in unambiguously identifying the hosts of physically small radio galaxies and highlights the need for high angular resolution data to unequivocally identify GSJ.

### 7.2 The Host Properties of GSJ

Whilst not part of the definition of GSJ, the sources I found in Chapter 4 are low-luminosity sources ranging between $3 \times 10^{22}$ and $1.5 \times 10^{25}$ W Hz$^{-1}$. The low luminosities suggest either that more powerful sources quickly pass through the GSJ stage or that their power increases with time so that higher luminosity sources are only observed after they have passed through the GSJ stage. In practice both scenarios may be true for different GSJ.

Morphologically, the radio jets of GSJ are a mixture of FRII and (predominantly) FRI types. The presence of FRII sources in the sample confirms other studies finding that low-power radio jets can produce an FRII-type morphology despite being below the traditional dividing line of Ledlow & Owen (1996). Mingo et al. (2019) find that these low-power FRII sources are in lower mass hosts so that for a given jet power, they are less likely to be disrupted. Whilst not contradicting this, my sample of low-power FRII sources is also too small to confirm it.

Whilst about 10 per cent of GSJ are found to be hosted by spiral galaxies, the majority are hosted by elliptical galaxies with properties similar to those found in larger radio galaxies (see Section 4.4.1). Overall, the spiral hosts are slightly smaller and bluer in colour than their elliptical counterparts though their number is sufficiently small that across the entire sample, the typical GSJ host properties remains consistent with those of a traditional ‘red and dead’ elliptical host. This suggests that the small size of GSJ is not caused by any of the observed host properties, though as has been suggested for the population of FR0s, a property that cannot be observed directly, such as black hole spin, may be relevant.

Overall the population of GSJ is substantial with about 10 per cent of all observed radio loud galaxies being classified as GSJ (Section 4.6). Identical to what is seen in larger radio galaxies, the likelihood of a galaxy hosting a GSJ is proportional to the mass of its supermassive black hole. The same relation is seen with respect to stellar mass for all but the most massive galaxies ($> 10^{11.5}$ M$_\odot$) where, contrary to what is seen in the general
AGN population, there is a decrease in the likelihood of a galaxy hosting a GSJ. Whilst the exact causes of this difference remain unclear it may be related to the tendency for larger galaxies to be found in denser environments where GSJ are less likely to be found (see Section 7.3).

### 7.3 The Environmental Properties of GSJ

Using optical catalogues of galaxy groups and clusters I found that GSJ are typically found in sparse environments similar to those of FR0 galaxies (Section 4.4.3). Using optical images, I also found no signs of mergers amongst the population of GSJ and whilst the image resolution makes it impossible to rule this possibility out, this does suggest secular processes are responsible for triggering activity in these low-luminosity sources.

These sparse environments are reflected in my X-ray studies of two GSJ where I detected the environment of one; ILT J120645.20+484451.1. For this source I found a bolometric X-ray luminosity of \(3.4 \pm 0.1 \times 10^{41} \text{ erg s}^{-1}\), which is towards the lower end of the range of environmental luminosities typically associated with radio loud galaxies. (Section 6.3.3.1). Whilst it is impossible to say how representative the environment of this source is of the general population, its low luminosity was found to be caused by a low electron density of \(335^{+46}_{-33}\) particles per cubic metre, which is again indicative of a sparse environment. The environment was however found to have a temperature of \(kT = 1.06 \text{ keV}\) which, whilst not unusual, is high for the type of group environment in which GSJ reside and, although I have found no evidence for this, may be the result of energetic feedback from the radio jets.

### 7.4 The Ages of GSJ

In Section 4.4.1.2, I found GSJ have a wide range of spectral indices. Whilst this cannot be used to age individual sources it does suggest that across the population as a whole GSJ have a range of ages with the smaller number of steep indices suggesting a correspondingly smaller number of older sources.

Amongst the total sample I found that GSJ with steeper integrated spectral indices tend to be physically larger. This is consistent with these sources being dominated by an older population of electrons. However, there are exceptions and some of the larger GSJ do have flatter spectral indices. It is possible that the larger sources with steeper spectral indices are simply expanding slower than those with flatter spectral indices and are therefore likely to remain in the GSJ stage for longer periods of time.

The possibility that some GSJ are young sources was confirmed in Section 5.7.3 where I obtained spectral ages for six of my sources. For these sources, the four FRI sources have ages between 5 and 20 Myr whilst the two FRII sources (both of which may have misidentified host galaxies) are older with ages between 40 and 60 Myr.
The spectral ages found for these six GSJ are older than those of compact CSS/GPS sources which typically have ages of a few thousand years. My results are therefore consistent with the theory that many compact sources are simply extremely young sources that will eventually evolve into larger radio galaxies. My results are also consistent with the general trend that for sources of a similar luminosity, larger sources will have older spectral ages.

During my spectral analysis I also found that some sources showed little variation in spectral age across the lobes. It is currently unclear whether this is due to different electron populations being caught in a single beam or whether, as simulations suggest, there is a significant amount of mixing of electron populations within these low-power sources.

In addition to these young sources, older GSJ are also expected and in Section 5.5.1 I found the first example of a remnant GSJ. However, whilst remnant sources are associated with older radio emission, it was not possible to age this source, so that this source may simply have been active for only a short period of time followed by a rapid fading of the radio emission. Despite this, the discovery of a remnant source does mean that at least some radio galaxies will never grow beyond the GSJ stage. Whilst currently unproven, these may be the large, steep spectrum sources seen in the total sample.

7.5 The Expansion Speeds of GSJ

In Section 5.8, I calculated the lobe expansion speeds for six of the GSJ that had been observed by the VLA. I found supersonic lobe advance speeds for four of my GSJ with the two spiral-hosted FRII sources showing sub-sonic advance speeds. These sub-sonic speeds are part of the evidence suggesting the host galaxies for these two sources may have been misidentified.

Assuming no acceleration then even at the maximum observed lobe advance speed found of $\sim 2500 \text{ km s}^{-1}$ (Section 5.8) it will take about $\frac{1}{2} \text{ Myr}$ for the lobes to expand by just 1 kpc. Therefore, whilst it is possible that all six sources will eventually grow beyond the GSJ stage, the lobe advance speeds found suggest that they are likely to stay in this stage for a long time.

Acknowledging that the speeds calculated are upper limits, the speeds observed for all six GSJ are toward the lower end of the range of speeds typically observed for radio galaxies, again suggesting that these sources are likely to spend a substantial amount of time in the GSJ stage. Despite this, the supersonic advance speeds do suggest that GSJ may be driving shocks into their environment.

However, shocks were not found for either of the two GSJ studied at X-ray wavelengths in Chapter 6. Whilst, as already mentioned, one of these sources is likely to have been misidentified, the lack of any detected shock for the other combined with the lobes requiring a significant proton contribution in order to reach pressure balance with the surrounding environment raise the possibility that, at least for this source, my lobe advance speeds could be significantly overestimated.
If my lobe advance speeds are wrong this could be because the assumption that the oldest age plasma found was emitted when the source first became active is wrong, or alternatively it may simply indicate that the rate of expansion has decelerated over time. Equally, whilst large, the proton content required to obtain pressure balance is not unheard of and large proton contents have been observed in a previous study of a single GSJ so that my estimates may be, as a first order estimate, reasonable in which case most GSJ are expected to be expanding fast enough to drive shocks into their host environment.

### 7.6 The Energetic Potential of GSJ

Under the assumption of a relativistic gas undergoing adiabatic expansion, I found that the total energy contained within the lobes is, on average, about a tenth of the total ISM energy within three times the host’s effective radius (Section 4.7).

In deriving my total energy estimates for FRI-type galaxies I initially calculated the total energy available under equipartition conditions assuming no proton content. Then, to account for the predicted proton content in FRI-type galaxies I multiplied my estimates by a factor of 10, as suggested by previous studies of large radio galaxies. However, my X-ray studies of one GSJ have shown that the proton content in the jets of GSJ may be higher than in larger radio galaxies (Section 6.4) so that the total energy available may be larger than estimated. My energy estimates also do not account for the existence of shocks, which again means that the total energy within the lobes of GSJ could be higher than estimated.

This supply of energy could have a significant effect upon the host; substantially reducing the gas cooling rate and the rate at which material is accreted into the central regions of the host galaxy. This would in turn affect the host’s star formation rate. It is even possible that the energy supplied by GSJ is responsible for driving a fraction of the host ISM out from the galaxy entirely.

Whilst I have not detected shocks for either of the two sources studied at X-ray frequencies (Section 6.3.1), meaning that it has not been possible to identify the location at which (at least some of) the energy is being transferred to the environment, the small physical size of GSJ suggests that energy transfer must be happening either within the host or in its immediate environment. This is supported by previous studies of GSJ which were found to be driving shocks into their host environment.

Since it is predicted that half the total energy transported by the jets will have been transferred into the environment at the point the jets turn off, my discovery of at least one remnant source (Section 5.5.1) also supports the argument that GSJ are depositing their energy into the host environment.
7.7 Future Work

7.7.1 GSJ at Intermediate Redshifts

This project uses the LOFAR Two Metre Sky Survey Deep Fields dataset (LoTSS-Deep, Tasse et al., 2021; Sabater et al., 2021; Kondapally et al., 2021; Duncan et al., 2021) to extend the identification of GSJ to intermediate redshifts and lower luminosities. Using these data, it will be possible to look for any indication of evolution of the galaxies in which GSJ are found.

LoTSS-Deep covers the ELAIS-N1 (Oliver et al., 2000), the Lockman Hole (Lockman et al., 1986) and Boötes (Jannuzi & Dey, 1999) fields and has a sensitivity of $\sim 25 \mu$Jy beam$^{-1}$ (compared to $\sim 70 \mu$Jy beam$^{-1}$ for LoTSS DR1) allowing identification of both extremely low luminosity and high redshift sources up to about $z \sim 2.5$. However, the 6 arcsec angular resolution of LoTSS-Deep (the same as LoTSS DR1) means it is predicted that it will not be possible to identify GSJ beyond $z \sim 1$ so that this project focuses on GSJ at intermediate redshifts and below.

Previous studies have argued that the space density of HERGs increases between $z = 0.5$ and $z = 1 - 2$ whilst the corresponding density of LERGs decreases over the same redshift range (Best et al., 2014; Williams et al., 2018) with the overall space density of radio galaxies peaking at around $z = 2 - 3$ where the number density of radio galaxies is two to three orders of magnitude greater than in the local universe (e.g. Schmidt, 1968; Rigby et al., 2011). This increase suggests that as redshift increases to this peak, increasingly lower mass hosts must be hosting AGN (Williams & Röttgering, 2015).

A preliminary analysis using data from SDSS DR14 (Abolfathi et al., 2018), reveals that 13 of the GSJ sample found in Chapter 4 are classed as high-excitation sources whilst the remaining 39 are low excitation according to the criteria of Buttiglione et al. (2010). The remaining objects had insufficient data to be classified. This suggests that both the number density of LERG GSJ will start to decline above $z \sim 0.5$ and that the proportion of HERG GSJ would increase. However, the progenitors of the current population of large, low redshift radio galaxies must have been smaller in the past which may suggest an increase in the number of GSJ at high redshifts. The implications for the population of high redshift GSJ are therefore presently unclear with this project looking for any evolution in the accretion mode of GSJ out to intermediate redshifts.

In the local Universe LERGs are predominantly in passive galaxies often referred to as being red and dead whilst HERGs are typically found in blue, star-forming galaxies (Heckman & Best, 2014). At high redshift LERGs are still found in passive galaxies whilst HERGs can be found in both passive and star-forming galaxies (Williams et al., 2018). This project would therefore also look for the first indications of any change in the host galaxy properties of GSJ at higher redshifts.

It was also found in Section 4.4.2.1 that a number of GSJ are hosted by spiral galaxies. Whilst it is not uncommon for spiral hosted galaxies, typically Seyferts, to host low-power radio jets ($L_{1.4GHz} \sim 10^{22}$ W Hz$^{-1}$) these are normally sub-kpc in size and are
confined within the host galaxy (Ulvestad & Wilson, 1989; Kinney et al., 2000; Momjian et al., 2003). At low redshifts, spiral-hosted GSJ therefore appear to be an intermediate population between these small-scale jets and the handful of spiral-hosted AGN hosting large kpc-scale radio structures that have been found (Ledlow et al., 1998, 2001; Keel et al., 2006; Hota et al., 2011; Bagchi et al., 2014; Mao et al., 2015; Mulcahy et al., 2016; Mao et al., 2018). It is possible that these types of objects may be more common at high redshift so that part of this project will look for any increase in the number of this fascinating class of object at higher redshifts.

### 7.7.2 GSJ in LoTSS DR2

This project would use a pre-release version of the second release of the LOFAR Two Metre Sky Survey (LoTSS DR2) to repeat the analysis in Chapter 4 using a far larger catalogue thereby providing more robust results. For a sub-sample of sources this project would also use LOFAR’s international baselines to study the 150 MHz radio output of GSJ at unprecedented angular resolution allowing identification of physically smaller GSJ than has hitherto been possible. At present the relation between compact sources and GSJ is unclear and so this sample will also allow the first study of the relationship between these classes of object.

LoTSS DR2 covers 5,634 square degrees (27 per cent) of the Northern sky and has detected 4,395,448 radio sources (Shimwell, in prep). It is predicted that a value-added catalogue will be publicly released in 2022 containing optical ID matches for over 73 per cent of the sources. Like DR1, the data used for the LoTSS DR2 survey were produced using the LOFAR stations within the Netherlands (see Section 3.1.1) so that both data releases are conducted at an angular resolution of 6 arcsec. However, unlike DR1, the data for LoTSS DR2 was recorded using all the international baselines and so it is possible to use the full LoTSS DR2 data set to produce images for individual sources at an angular resolution of 0.27 arcsec (Morabito et al., 2022).

Whilst the GSJ studied in this thesis are larger and less luminous than GPS/CSS sources (O’Dea & Saikia, 2021), they are of comparable luminosity to the Low Power Compact (LPC) radio galaxies studied by Giroletti et al. (2005) as well as the Low Luminosity Compact (LLC) sources of the CORALZ sample (Snellen et al., 2004), albeit with larger sizes. Therefore, as well as providing a more robust analysis of the results from Chapter 4, this project would produce high angular resolution images from the LoTSS data for a sub-sample of GSJ selected to represent the range of sizes and luminosities observed. Using these sub-arcsecond resolution images it will be possible to better identify any sub-components within GSJ, to measure the corresponding flux densities and compare them with compact sources.

At present the small size of compact sources, such as the LPC and LLC sources, is typically attributed to one (or more) of the following reasons (O’Dea & Saikia, 2021):

- Young Age
• Frustration

• Transient or intermittent sources

For individual sources high angular resolution radio morphology, such as would be produced in this project, can help distinguish between these possibilities. For example, young sources expanding out through an inhomogeneous, asymmetric medium will often exhibit structural and polarization asymmetries between the two jets (as seen in many of the objects from the CORALZ sample Kunert-Bajraszewska et al., 2010; Kunert-Bajraszewska & Labiano, 2010; Kunert-Bajraszewska et al., 2014; Kunert-Bajraszewska, 2016). In contrast frustrated jets (e.g. 3C 48) often show complex structures due to the jet being deflected and/or disrupted. Transient/intermittent sources may exhibit a sudden break in the radio spectral properties between the young and old emission, though it should be noted that the flux density of any old emission will depend upon a combination of how long the source has been inactive (i.e. its duty cycle), how quickly the older emission fades and the sensitivity of the observation.

Should any GSJ be found to have an asymmetric or complex radio morphology this would not only imply a relation with compact sources, it will also indicate that the jets are being disrupted/deflected by the host ISM and provide direct evidence of feedback between GSJ and their hosts.

Combined with multi-frequency data, it will also be possible to calculate either the turnover frequency or an upper limit for this sub-sample of GSJ. This will allow the size-turnover relation seen in samples of compact objects such as CORALZ (de Vries et al., 2009; Jeyakumar, 2016) to be tested against the physically larger population of GSJ, looking for any indications of the size/power at which this relation no longer holds.

7.7.3 The Cores of GSJ

This project would use the international baselines available for LoTSS DR2 to look at the radio cores of nearby GSJ at milli-arcsecond angular resolution, examining the relation between small scale and large scale radio structures, looking into the possible evolutionary relation between compact sources, GSJ and the larger FRI/FRII galaxies and examining the accretion properties of GSJ.

The GSJ found in this work are low luminosity sources (see Section 4.4.1) which are expected to have correspondingly low-power jets which could be more easily deflected via interactions with the host galaxy. Such interactions may provide points at which energy can be transferred from the jets directly into the host, potentially increasing the impact these sources could have upon the host galaxy’s evolution. Since LoTSS international baseline data are not available for the sources studied in this thesis, this project would initially use the methods introduced in this thesis to identify GSJ from the 6 arcsec resolution LoTSS DR2 value added catalogue. Using the LoTSS international baselines, high angular resolution images would then be produced for a sub-sample of GSJ with sufficiently low redshifts for parsec-scale structures to be visible at the 0.26 arcsec resolution of LoTSS-VLBI (Morabito et al., 2022).
This project would then use these observations to study the core morphology and alignment of GSJ, allowing a comparison with the radio lobes seen in LoTSS providing, for the first time, an indication of the extent of interaction between the host galaxy and its radio jets.

It will also be possible to get the first measurements of the core radio powers of this class of object. Previous work has found a similar relation between the optical [OIII] line luminosity and radio core power for LINERs, FRI radio galaxies and HII star-forming galaxies with jets. In comparison Seyferts show an excess of [OIII] according to this relation and non-jetted HII galaxies have lower [OIII] luminosities (e.g. Baldi et al., 2018a). A preliminary study of the GSJ sample described in Chapter 4 reveals that according to the criteria of Kewley et al. (2006), GSJ are primarily LINERs with some HII star-forming galaxies and a very limited number of Seyferts. Combining measurement of the radio luminosity with archival optical information from the SDSS (Abolfathi et al., 2018), it will be possible to use GSJ to test the relation between optical line luminosity and core radio power for the population of physically small radio galaxies.

The fundamental plane of black hole activity (FPBHA) is a relation between the core radio, X-ray luminosities and black hole mass, though the [OIII] emission line is often used as a proxy for X-ray luminosity (Merloni et al., 2003). Whilst still debated (e.g. Plotkin et al., 2012; Bonchi et al., 2013), it does suggest that regardless of the accretion mode, the accretion-jet relation is scale invariant. When plotted on the FPBHA, Seyferts and LINERS follow the same trend with Seyferts being in an intermediate position between jetted LINERs and radio quiet Quasars. This trend continues all the way up to FRI radio galaxies. Using LoTSS-VLBI observations, it will be possible to analyse the location of GSJ on this plane and to compare them with previous samples.

Using the LoTSS-VLBI data it will also be possible to study the nuclear accretion and to disentangle it from star formation related emission providing an insight into the interplay between the AGN and the host’s core in this class of object. All the GSJ studied in this thesis contain low-luminosity AGN (LLAGN) according to the criteria $L_{\text{H}\alpha} < 10^{40}$ erg s$^{-1}$ (Ho et al., 1997). Theoretical studies show that both LLAGN and more powerful AGN have similar nuclear and jet properties (Begelman et al., 1984; Falcke & Biermann, 1999; Beckwith et al., 2008; Massaglia et al., 2016) where advection-dominated accretion flows (ADAF, Narayan et al., 2000) are predicted to be generating jets at low accretion rates. At higher accretion rates an optically thick, geometrically thin accretion disc is expected sometimes referred to as a Shakura Sunyaev Disc (SSD, Shakura & Sunyaev, 1973) which are less efficient at producing jets than ADAF discs.

For LLAGN classed as LINERS, the relation between the optical [OIII] line luminosity and radio core power coupled with low Eddington rates is often taken as evidence of an ADAF disc. In contrast Seyfert-like LLAGN typically have high emission line ratios, large [OIII] luminosities and an [OIII] excess in the [OIII]-core radio luminosity plane compared to LINERS which is normally interpreted as evidence of an SSD (e.g. Baldi et al., 2018a). Unlike purely optical classifications which require detection of multiple emission lines, many
of which are poorly constrained for GSJ, this will provide a more reliable indication of the accretion mode for GSJ. The low-luminosity of the GSJ found in this work also means star formation-related emission is less likely to be dominated by AGN-related emission so that this class of object may provide an ideal opportunity for studying the transition between accretion modes.

Finally, it will also be possible to compare the core radio power with the physically smaller, less powerful radio galaxies studied in the LeMMINGs survey (Baldi et al., 2018a, 2021) as well as both the population of compact sources (O’Dea & Saikia, 2021) and FR0s (Baldi et al., 2015, 2018b). This will provide a clearer understanding of how these classes of objects relate to each other and any possible evolutionary sequence between them.

7.8 Summary

I have used data from LoTSS DR1 to discover a population of 195 GSJ with total physical sizes less than 80 kpc. Using this sample, I have discovered that GSJ are preferentially found in sparse/group environments and are hosted by massive galaxies whose properties are typical of the wider population of radio loud galaxies.

The GSJ stage forms a substantial and important part of the life cycle of radio loud AGN with about 10 per cent of all radio loud galaxies being classified as GSJ. Whilst evolution of CSS/GPS sources into larger FRI/FRII sources is still debated, the size and age of GSJ are consistent with being at an intermediate stage along this evolutionary path. Many GSJ are therefore predicted to grow into larger FRI/FRII-type galaxies although my discovery of at least one remnant GSJ suggests that some sources will never grow beyond the GSJ stage.

I have shown that the total energy contained within the lobes of GSJ is capable of having a significant impact upon the evolution of the host. I have also investigated the particle content of one GSJ’s lobes finding that, like previous studies, it has a large proton content which has probably been entrained from the surrounding environment and which suggests a large interaction between GSJ and their host environments.

Using high angular resolution radio data to obtain the lobe expansion speeds for a sub-sample of six sources I predicted that the majority of GSJ are driving shocks into their environment meaning that my total energy estimates are a lower estimate. However, I did not detect any shocks in the two GSJ studied at X-ray wavelength and was therefore unable to confirm my expansion speeds so that they remain as upper limits.

I have also suggested some future projects that would enhance our understanding of the GSJ class of radio galaxies and the conclusion of this thesis; that energetic feedback from physically small, low luminosity, radio galaxies is potentially capable of having a significant effect upon the evolution of the host.
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