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CHAPTER 1

Introduction

1.1 Active Galactic Nuclei

Just over fifty years ago, Schmidt (1963) associated the radio source, 3C273, with an optically unresolved source at the then extreme redshift, of z 0.158. This was shortly followed by the discovery of a population of such quasi-stellar radio sources (quasars) at even higher redshifts and a similar population of quasi-stellar galaxies (Sandage 1965). It is now understood that the fundamental property of these sources, called Active Galactic Nuclei (AGN), is that they are powered by gas falling into the relativistically-deep potential well of black holes with masses of millions to billions that of the Sun. Such supermassive black holes (SMBHs) lie at or near the centres of (probably) all galaxies. The observational characteristics of traditional AGN are diverse and may include an incredibly high luminosity, emission on very small angular scales, broadened emission lines, variability, radio emission, the presence of jets, and polarised emission. Compared to a normal galaxy, a typical AGN may have excess ultraviolet, infra-red and X-ray emission resulting in a flat broadband spectrum. However, any given AGN may exhibit only a selection of these features and different classifications of AGN over the years have created a 'zoo' of objects. Over the past fifty years our understanding of AGN has been built up into a unified model in which, the observed features are heavily dependent on viewing angle, the mass of the central black hole and the accretion rate of the black hole (e.g. Antonucci 1993).

Up to the eighties, these AGN were merely interesting laboratories for the study of extremely high-energy physical processes, and their role in the evolution of galaxies was not yet realised. However, the accumulation of observational evidence, while still largely indirect, has led to the now widely accepted notion that AGN play a crucial role in the evolution of galaxies and are necessary to produce the observed properties of galaxies in the contemporary Universe. Firstly, AGN are more numerous than originally thought, with many more weaker AGN. This leads us to understand that they play an important role in the lifecycle of galaxies. Secondly, the growth of galaxies, as traced by their star formation histories, and the growth of SMBHs, traced by AGN, are remarkably similar. Both show an increase to z 1, with a peak at $z \sim 2 - 3$ (e.g. Shankar et al. 2009). Moreover, the masses of the SMBHs in massive galaxies are correlated with various properties of their hosts. These properties include the galaxy luminosities (e.g. Kormendy & Richstone 1995; Marconi & Hunt 2003; Gültekin et al. 2009), the galaxy bulge masses (e.g. Magorrian et al. 1998; McLure & Dunlop 2002) and the velocity dispersions (e.g. Ferrarese & Merritt 2000; Gebhardt et al. 2000; Merritt & Ferrarese 2001). Finally, the antihierarchical evolution of AGN (e.g. Miyaji et al. 2000; Hasinger et al. 2005; Bongiorno et al. 2007; Rigby et al. 2011), i.e. the fact that the space density of low-luminosity AGN peaks around $z < 1$ and that of high-luminosity AGN peaks around $z \sim 2$, is very similar to the cosmic downsizing of star-forming galaxies (e.g. Cowie et al. 1996; Menci et al. 2008; Fontanot et al. 2009) and spheroidal galaxies (e.g. Cimatti et al. 2006).

At least out to $z \sim 2$, galaxies are observed to have a clear bi-modal distribution (Kauffmann et al. 2008; Blanton et al. 2003; Baldry et al. 2004). The first population is that of blue galaxies. These tend to have lower stellar masses (M_*) and have high star formation rates (SFR). In general more massive blue galaxies have higher SFR. The second population is called red and dead, owing to their minimal star formation activity. These are preferentially more massive galaxies. Broadly, galaxy evolution can be sketched as the following (e.g. Lilly et al. 2013): a galaxy starts its life on the blue star-forming sequence and it gradually gains mass by accreting gas from the cosmic web and via mergers with other galaxies. At some point, star formation ceases when its supply of gas becomes cut off, in a poorly understood process called quenching, and the galaxy evolves onto the red sequence. Red galaxies usually only increase in mass through further mergers. Numerical and semi-analytical models of the formation and evolution of galaxies show that additional processes are necessary to explain the present day massive galaxy population. In particular AGN provide a means to either heat or eject the surrounding gas and prevent further star formation from cold gas.

1.1.1 Accretion Modes

Over the last decade a more complete picture has emerged of the population of AGN in the present-day Universe. In this picture, the AGN population is split in two categories, with the division between them based on their accretion rates and distinct in the SMBH and host galaxy properties. In the first class, the dominant energy output is in the form of electromagnetic radiation from the efficient conversion of potential energy when gas in accreted by the SMBH. This is referred to as the 'radiative-mode'. Historically, they have been called Seyferts or QSOs depending on their luminosity. The second class produces little electromagnetic radiation and the energy output is primarily in the form of bulk kinetic energy carried by collimated jets. Consequently, these are usually referred to as 'jet-mode' AGN. A schematic overview of the two classes is shown in Fig. 1.1 and their observational characteristics and fueling mechanisms are described in the following sections.

Radiative-mode

In these AGN, inflow on to the SMBH occurs via a geometrically thin, optically thick accretion disk (Shakura & Sunyaev 1973). Thermal continuum emission from the accretion disk is produced spanning from the extreme ultraviolet (UV) through the optical. A corona of hot gas produces X-ray emission through Compton scattering of light from the disk. Radiation from the disk and corona heats and photoionises gas in the vicinity. Closer to the SMBH, where the velocity dispersion of the gas is a few thousands km/s, this produces broad emission lines in the UV, optical and near-infrared (NIR). More tenuous gas at greater distances, results in both forbidden and permitted emission lines, with narrower linewidths (hundreds of km/s). These give rise to, respectively, the broad-line region (BLR) and narrow-line ragion (NLR). The presence of a larger-scale dusty molecular gas structure may, in some cases, inhibit views of certain emission by absorbing soft X-ray, UV and visual light. This dusty structure re-radiates the ab-

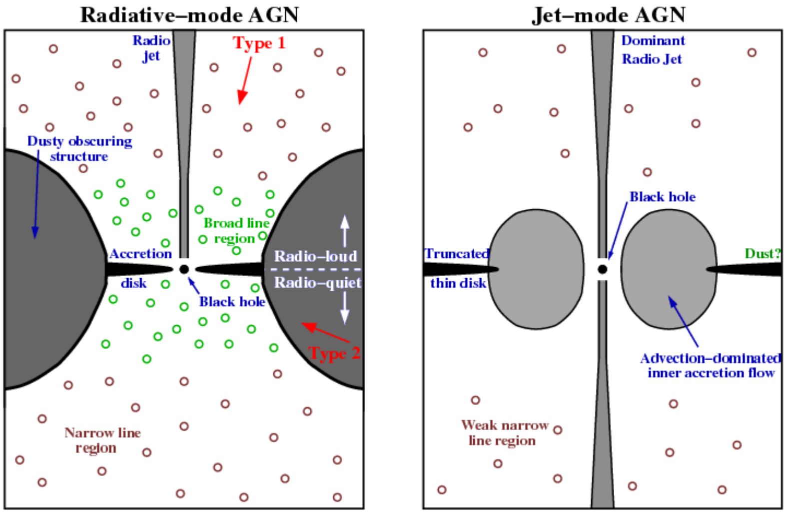

Figure 1.1: Schematic drawings of the central engines of AGN in the radiative mode (*left*) and jet mode (*right*). Radiative-mode AGN have a geometrically thin, optically thick accretion disk, illuminating the broad- and narrow-line regions with UV radiation. At some viewing angles, a dusty, obscuring structure may inhibit the view of the accretion disk and broad-line region (Type 2 AGN). While at other angles, these features are visible (Type 1 AGN). A small fraction of these sources produce powerful radio jets. Jet-mode AGN lack the accretion disk, having instead a geometrically thick ADAF. Radio jets release the majority of the energy output in the form of bulk kinetic energy. (Image reproduced from Heckman & Best 2014).

sorbed light as thermal emission in the mid-infrared (MIR). In the unified models (e.g. Barthel 1989; Antonucci 1993; Urry & Padovani 1995), the angle at which the source is viewed results in different features being seen. Sources which are not obscured have been referred to as Type 1, while obscured sources are called Type 2 and may lack broad emission lines, soft X-ray emission and optical emission from the disk. In some cases, even the hard X-ray emission can be obscured. A small fraction of these sources produce collimated jets, leading to radio emission. The key observation that led to the adoption of unified models for powerful radio galaxies and radio-loud quasars was that all quasars appear to be beamed towards us (Barthel 1989). These sources have been called quasi-stellar objects (QSOs) or Seyferts, depending on the luminosities. The nomenclature for this mode includes 'Quasar mode', 'cold mode', 'fast-accretor', 'high excitation', or 'strong-lined'. Radio sources in the radiative-mode have been found to be typically hosted by lower mass, bluer galaxies in less dense environments (e.g. Tasse et al. 2008; Janssen et al. 2012).

The most widely suggested triggering mechanism for radiative-mode AGN activity is through major mergers or strong tidal interactions (e.g. Kauffmann & Haehnelt 2000; Hopkins & Beacom 2006; Hopkins et al. 2008). Mergers are indeed known to trigger starbursts (e.g. Larson & Tinsley 1978). However, there is contradictory evidence which suggests that there is no enhanced AGN activity in mergers identified either by galaxies with close companions (e.g. Li et al. 2008) or through their morphology (e.g. Reichard et al. 2009). Another proposed fueling mechanism is through secular processes (disc instabilities, minor mergers, recycled gas from dying stars, galaxy bars etc.), in particular for low-luminosity AGN (e.g. Genzel et al. 2008; Johansson et al. 2009; Ciotti et al. 2010). It remains clear, however, that what is needed to produce radiative-mode AGN activity is an abundant central supply of cold dense gas (e.g. Larson 2010).

Jet-mode

The second class of AGN either lack or have a truncated accretion disk. Instead, accretion occurs on timescales shorter than the radiative cooling time by means of a geometrically thick structure. Gas is accreted in advection dominated or radiatively inefficient accretion flows (ADAFs or RIAFs, e.g. Narayan & Yi 1994, 1995; Quataert 2001; Narayan 2005; Ho 2008). This results in two-sided relativistic jets, which may extend from a few parsecs to megaparsec scales. These sources do not show the luminous narrow lines expected in the framework of AGN unification (e.g. Hine & Longair 1979; Laing et al. 1994; Jackson & Rawlings 1997). They also lack the expected infrared emission from a dusty torus (e.g. Whysong & Antonucci 2004; Ogle et al. 2006) and do not show accretion related X-ray emission (Hardcastle et al. 2006; Evans et al. 2006). They lack the strong emission lines of the radiative-mode AGN, but may exhibit some weak narrow lines (called LINERs). Jet-mode AGN nomenclature includes 'radiatively inefficient', 'radio-mode', 'hot-mode', 'weak lined', 'slow-accretor', and 'low excitation'. Best et al. (2005a) showed that jet-mode radio galaxies are hosted by fundamentally different galaxies: higher mass, redder and occurring in more dense environments. This mode in particular provides a direct feedback connection between the AGN and its hot gas fuel supply in the manner of work done by the expanding radio lobes on the hot intra-cluster gas.

The fuel source of jet-mode AGN has been argued to be hot gas (e.g. Hardcastle et al. 2007). The source of this hot gas has long been postulated to be shed from old stars (e.g. David et al. 1987; Norman & Scoville 1988; Ciotti & Ostriker 1997; Kauffmann & Heckman 2009). These sources are generally found to be in massive galaxies in the centres of groups and clusters, whose hot gaseous X-ray emitting haloes provide a source of fuel.

1.1.2 Radio AGN

Radio continuum observations are an important means to find AGN, particularly those in the jet-mode. Also, because the dusty obscuring structure is transparent to the radio, radio-emitting Type 2 radiative-mode AGN are detectable in radio surveys. As with studying AGN at other wavelengths, radio observations have their problems. These include complications in identifying the optical host galaxies, because the jet emission and source are not coincident, and confirmation that the radio emission is indeed from the AGN instead of star formation processes. Radio-loud objects are notably important to our understanding of AGN. Despite the fact that they constitute only a small fraction of the overall population, it is during this phase that the impact of the AGN on their surrounding environment (through the production of jets and large-scale outflows and shocks) can be most directly observed and measured (e.g. Kraft et al. 2003; Cattaneo & Best 2009; Croston et al. 2011). Moreover, radio galaxies make up over 30 per cent of the massive galaxy population, and it is likely that all massive galaxies go through a radio-loud phase, as the activity is expected to be cyclical (e.g. Best et al. 2005b; Saikia & Jamrozy 2009).

The radio emission from AGN is synchrotron radiation, arising from relativistic electrons spiraling around magnetic field lines, both of which likely originate near the central SMBH (Rees 1978; Blandford & Payne 1982). The exact mechanism responsible for the production of relativistice jets in some AGN are not understood due to the low resolution of current observations, which cannot provide enough evidence to favour one of the various theoretical models of jet production over the many that exist. Indeed, much progress has been made in semi-analytical models and magneto-hydronamic simulations of jets since black holes were first postulated to be a source of high energy particle jets (e.g. Blandford & Znajek 1977; Williams 1995; Falcke 1996; Vlahakis & Königl 2003; Polko et al. 2010). However, the synchrotron emission is well understood and has a characteristic power-law spectral shape, $S_\nu \propto \nu^\alpha$ over decades in frequency (e.g. Klamer et al. 2006), where the spectral index, α, is typically ≈ -0.8 (e.g. De Breuck et al. 2000). Thus, radio observations of AGN can benefit from the increased brightness towards lower observing frequencies. At the lowest frequencies though the spectrum flattens due to synchrotron self-absorption or free-free absorption Rybicki & Lightman (1979). At lower frequencies, the lower relativistic energy of the emitting particles results in a longer synchrotron lifetime. The observed, as opposed to intrinsic, duty cycle[1] of radio activity is thus longer. A small population of sources have ultra-steep spectra (USS; $\alpha \lesssim -1.3$). It has long been realised that in flux-limited radio surveys, sources with the steepest spectra are systematically at higher redshifts (e.g. Tielens et al. 1979; Blumenthal & Miley 1979). Selection of such sources has resulted in the discovery of the most distant radio galaxies (Miley & De Breuck 2008).

Historically, radio loud resolved jet-dominated sources have been separated in two classes, largely defined by their apparent morphology, Farnaroff-Riley class I and II (Fanaroff & Riley 1974). FRI, or edge-darkened, sources tend to display luminosities which peak close to the galaxy core, and may include disturbed or anisotropic radio structures. FRII, or edge-brightened, sources have well defined morphologies, with clear lobes and outer hotspots, and jets that are more collimated in general than FRIs. Both FRIs and FRIIs span a wide range in radio luminosity with significant overlap. However there is a rough critical power, $P_{1.4\mathrm{GHz}} \sim 10^{24}\ \mathrm{W\,Hz^{-1}}$, above which most sources are FRII and below which most are FRI (Best 2009; Gendre et al. 2010). The most popular interpretation of the difference between FRI and FRIIs is that it can be explained by the density of the Intergalactic Medium (IGM) in which they exist. Jets produced by the central engine will be disrupted, and reach very much shorter distances due to entrainment (mixing) of the surrounding medium in regions of high density IGM, producing FRIs. The denser the environment, the more powerful the jet is needed to be in order to prevent disruption, and produce a classic FRII. However, the reasons for the divide may not be solely confined to this simple idea, as FRIIs have been found in clusters, i.e. regions of high density IGM (e.g. Wan & Daly 1996).

An alternative scheme is to separate radio AGN by their accretion types, which are more directly linked with their feedback modes. Indeed, there two distinct populations revealed by radio surveys. The first is associated with strong classical QSOs (i.e. radiative-mode), historically called 'high excitation radio galaxies' (HERGs). The second is a population of weak LINER-like sources (i.e. jet-mode), called 'low excitation radio galaxies' (e.g. Hine & Longair 1979; Laing et al. 1994). In the local Universe it has been shown by Best & Heckman (2012), that 95 per cent of low-luminosity radio AGN ($P_{1.4\mathrm{GHz}} \lesssim 10^{25}\ \mathrm{W\,Hz^{-1}}$) are jet-mode LERGs, while radiative-mode HERGs start to dominate at high powers ($P_{1.4\mathrm{GHz}} \gtrsim 10^{26}\ \mathrm{W\,Hz^{-1}}$). Because of the similar limiting power, there is some overlap between the FR classification Gendre et al. (2013), but it is not one-to-one with samples of jet-mode FRIIs (e.g. Laing et al. 1994) and a small population of radiative-mode FRIs (e.g. Heywood et al. 2007).

Radio samples derived from large spectroscopic surveys provide an excellent means to study the radio AGN population in the two modes. Such samples have reinforced the idea that LERGs or jet-mode sources are hosted predominantly by red massive ellipticals at the centres of groups or clusters, while HERGs or radiative mode radio sources are hosted by bluer star-forming galaxies

[1] i.e. the observed ratio in time between when the radio source is 'on' to when it is 'off.'

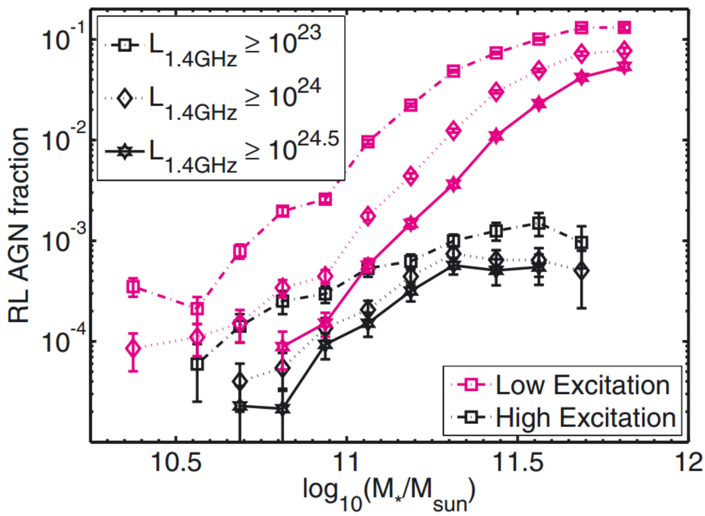

Figure 1.2: The fraction of radio AGN as a function of their host galaxy stellar mass. Low excitation, or jet-mode, sources show a much flatter dependence on stellar mass than high excitation, or radiative-mode, sources. Largely independent of the radio-power cutoff. (reproduced from Janssen et al. 2012).

(e.g. Best & Heckman 2012; Janssen et al. 2012; Gürkan et al. 2014). In particular, studies by Best & Heckman (2012) used such a sample to derive the Eddington ratios for the radio sources in the radiative and jet-modes by calculating the total jet energy output in the form of mechanical energy and the total bolometric radiative luminosity. They find that the two populations are distinct in their Eddington-scaled accretion rates, with the jet-modes sources accreting at $<$ 1 per cent of the Eddington rate, and radiative-mode sources accreting at $1 - 10$ per cent of the Eddington rate. Similarly, Janssen et al. (2012) show that the prevalence of radio AGN activity as a function of host stellar mass and colour is different for HERGs and LERGS. In particular, the fraction of LERGs is a much steeper function of host stellar mass ($f_{\mathrm{LERG}} \propto M_*^{2.5}$) than for HERGs ($f_{\mathrm{HERG}} \propto M_*^{2.5}$). This is shown in Fig. 1.2.

1.1.3 Feedback Processes

To explain the observed co-evolution of black holes and their hosts, theoretical models invoke 'feedback' between the SMBH and the gas and dust within the host galaxy (e.g. Granato et al. 2004; Springel et al. 2005; Croton et al. 2006; Hopkins et al. 2006; Sijacki et al. 2009; Cen & Chisari 2011). Models often represent the effects of feedback in two ways, denoted 'quasar mode' and 'radio mode' (e.g. Croton et al. 2006), related to the accretion modes described above. In the quasar mode, energy is released as winds driven by the radiative output of AGN. The radiation interacts with gas and dust in the host galaxy. The resulting winds can expel gas from the galaxy, thus stopping the accretion of matter on to the black hole and further quenching star formation (e.g. Page et al. 2012). However, studies of X-ray luminous AGN do not show any evidence for this (e.g. Harrison et al. 2012). In radio-mode feedback, the jets may play an important role in the evolution of the host galaxy by heating up the cold gas and suppressing star formation (e.g. Best et al. 2005a; Hardcastle et al. 2013). In the most dramatic scenario, the jets can expel the molecular gas from the host galaxy. Radio-mode feedback has been widely used in simulations as a mechanism usually to prevent the overproduction of stars in massive galaxies, to produce the observed 'red and dead' galaxies (e.g. Bower et al. 2006; Werner et al. 2014). However, a positive radio-mode feedback has also been suggested (e.g. Silk & Nusser 2010; Gaibler et al. 2012; Kalfountzou et al. 2012). In this 'jet-induced star formation', the radio jets drive shocks in the interstellar medium which enhance the star formation, which has already been observed (e.g. Blanco et al. 1975; van Breugel et al. 1985; McCarthy et al. 1987; Chambers et al. 1987; Eales & Rawlings 1990; Best et al. 1998; Inskip et al. 2005).

1.2 Low Frequency Radio Astronomy

In 1931 astronomy was revolutionised with the first major extension of observations beyond the optical, near-ultraviolet and near-infrared. This occurred when Jansky (1933) made the first serendipitous discovery of a source of extra-terrestrial emission using an antenna operating at radio frequencies of 20.5 MHz. This emission, designated Sagittarius A, is now known to originate from the Galactic centre. Shortly thereafter Reber (1940) detailed the first radio map of the Galactic plane and large portions of the sky with observations at 160 MHz. Among the first important scientific discoveries was that of the first extragalactic radio source, Cygnus A, (Baade & Minkowski 1954) and that of the first QSO, 3C283, (Schmidt 1963).

Radio astronomy developed rapidly in the early years, with significant early technological milestones achieved with the first astronomical observations with a two-element radio interferometer (Ryle & Vonberg 1946) and the first use of earth rotation synthesis (Ryle 1962). During this time several low frequency surveys were conducted with the Cambridge interferometry 3C, 4C, 6C and 7C at 159, 178, 151 and 151 MHz, respectively (Edge et al. 1959; Bennett 1962; Pilkington & Scott 1965; Gower et al. 1967; Hales et al. 1988, 2007) building up the ever larger samples radio sources leading to greater understanding in particular of quasars and AGN. While many of the earliest radio telescopes operated at low frequencies ($\lesssim$ 200 MHz), the development over the past fifty years has largely been towards higher frequencies ($\gtrsim$ 1400 MHz) in the pursuit of higher sensitivities and higher angular resolution.

The last decade has seen a substantial growth in the number and diversity of radio synthesis telescopes being constructed, as a lead up to the Square Kilometre Array (SKA; Schilizzi 2005). Examples include the Expanded Very Large Array (EVLA; Perley et al. 2004), the Australian Square Kilometre Array Pathfinder (ASKAP; Johnston et al. 2007), and the Karoo Array Telescope (MeerKAT). Additionally, faster computers mean it is now possible to correlate signals from hundreds to thousands of individual antennae, making it possible to build large arrays of dipoles. This has led to a rejuvenation in low-frequency radio astronomy with several new arrays being built, including the Long Wavelength Array (LWA; Taylor 2007), the Murchison Widefield Array (MWA; Lonsdale et al. 2009; Tingay et al. 2013), and the Low Frequency Array (LOFAR; van Haarlem et al. 2013).

LOFAR is a new low frequency radio telescope in the Netherlands and surrounding European countries. Its revolutionary design makes use of phased arrays instead of the traditional and expensive dishes, which are turned into a real telescope electronically. The array is composed of several 'stations' each containing a number of simple dipoles. There are two types of dipole antennas, one for the Low Band Array (LBA) operating at 10–80 MHz and one for the High Band Array (HBA) operating in the 110–240 MHz range. The Dutch part of the array consists of 37 stations going out to 80 km. The array is extended to baselines of up to 1200 km with a fur-

Figure 1.3: The LOFAR superterp near Exloo, Netherlands, showing several stations with both HBA and LBA antennae (*left*). Individual LBA (*top right*) and HBA (*bottom right*). (credit LOFAR/ASTRON).

ther eight stations in a number of other European countries. The signals from the antennas are digital, meaning that many beams or pointings can be formed simultaneously. This, combined with its large instantaneous field-of-view, makes LOFAR an extremely efficient instrument for surveying large areas of the sky. The electronic nature of the beams makes LOFAR highly flexible. In terms of frequencies, a total bandwidth of up to 95 MHz is available. The Dutch array provides resolutions of a few tens of arcsec at 60 MHz and a few arcsec 150 MHz, unprecedented for these frequencies. The inclusion of international baselines gives sub-arcsecond resolution in both the low and high bands. Fig. 1.3 shows an image of the central collection of six stations, the 'superterp', and close-up images of individual LBA and HBA dipoles.

These telescopes bring both new scienctific and new technical challenges. These challenges include developing new theories to describe effects which were previously ignored and algorithms to solve the resulting equations. This requires a significant increase in the performance of these algorithms in order to produce the best possible sensitivity and dynamic range. Practically, the new instruments demand the ability to handle the large increase (of factors of hundreds or thousands) in data volume, which in turn requires high performance computing and faster calibration and imaging algorithms. Radio astronomy has progressed significantly since the first radio images of the sky were made. In particular in the area of calibration, whereby instrumental effects are corrected. The first major advance in calibration was the introduction of self-calibration (e.g. Pearson & Readhead 1984), which allows one correction per antenna per polarisation. Low frequency observations necessarily lead to wide fields of view and greater effects of the ionosphere. This requires corrections to be made which vary across the field-of-view. In recent years, significant progress has been made in the field of direction-dependent calibration, including field-based calibration (Cotton et al. 2004), Source Peeling and atmospheric modeling (SPAM Intema et al. 2009; Intema 2014) and SAGECal (Yatawatta et al. 2013; Kazemi et al. 2011). Additionally, high performance algorithms to solve the calibration equations have been developed such as Statistically Efficient and Fast Calibration (stefcal; Salvini & Wijnholds 2014) and the use of Kalman filters (e.g. Smirnov & Tasse 2015). Improvements in imaging techniques have also been needed as some of the assumptions made in early radio image break down. These include techniques such as w-projection (Cornwell et al. 2008) and A-projection (Bhatnagar et al. 2008) in imaging, and the development of new imaging software which take these into account (e.g. Tasse et al. 2013).

1.3 This Thesis

One of the most fundamental issues in understanding the role of AGN in galaxy formation is the need to accurately measure the cosmic evolution of quasar activity and the accretion history of the Universe, and to compare this with the build-up of the stellar populations of galaxies: do black holes and their host galaxies grow coevally, or does one precede the other? what is the primary mode of black hole growth? The majority of the growth of SMBHs and the stellar component of galaxies occurs between redshifts of about 0.5 and 2. Their present day growth is an order of magnitude lower than it was at their peak. To properly understand the detailed process of galaxy formation and evolution the physical processes involved in 'AGN feedback' need to be identified and quantified. Current radio and spectroscopic surveys have greatly increased our understanding of the contemporary population of AGN. While these sources contain a fossil record of their histories, to fully quantify the effect of AGN, it is necessary to extend such work back to earlier cosmic epochs where the AGN and star-formation activity of the Universe peaked. With the more powerful radio telescopes now available, it is now becoming possible to directly study the AGN population at these redshifts. To this end, in this thesis we aim to answer the following:

1. How does the relationship between galaxy mass and radio AGN fraction, i.e. the radio source duty cycle, evolve with redshift?
2. How does the radio AGN population evolve with redshift?
3. What is relationship between host galaxy properties and radio AGN at redshift $0.5 \lesssim z \lesssim 2$?

In this thesis the redshift evolution of radio-loud AGN is studied. The main tool for these studies is deep, high-resolution, low frequency imaging of fields with excellent complementary data. The first part of this thesis (Chapters 1 to 3) uses the most advanced calibration techniques to provide low-frequency radio images using the GMRT and LOFAR. The latter part of the thesis (Chapters 4 and 5) combine radio samples with optical data to study host galaxy properties of radio-loud AGN over cosmic time.

Chapter 2 presents a wide area, deep, high-resolution 153 MHz GMRT observations of the NOAO Boötes field (Jannuzi & Dey 1999). This extragalactic deep field has been extensively studied at optical, ultraviolet and mid-infrared wavelengths. The low frequency radio data have been calibrated for direction-dependent ionospheric effects with the SPAM package (Intema et al. 2009). The GMRT mosaic image includes seven pointings, covering a total of 30 square degrees, at a resolution of 25 arcsec and achieves an rms noise of $2-5$ mJy beam^{-1}. The extracted source catalogue contains 1289, of which 453 are resolved. Monte-Carlo routines for determining the completeness and reliability of radio catalogues are developed. Euclidean-normalized differential source counts and spectral index distributions were calculated.

In **Chapter 3** we present the first LOFAR Low Band Antenna (LBA) observations of the Boötes and 3C 295 fields at 34, 46, and 62 MHz, covering an area of 17 to 52 square degrees. The images presented are the deepest images ever obtained in this frequency range at noise levels of 12, 8, and 5 mJy beam^{-1} in the three frequency bands. Source extraction yielded 300–400 sources in each of the images. Source counts are again derived with the 62 MHz source counts agree with previous GMRT 153 MHz and VLA 74 MHz differential source counts, scaling with a spectral index of -0.7. The lower frequency 34 MHz source counts, suggest that the average spectral index of radio sources flattens towards lower frequencies. The average spectral index of sources between 34 and 1400 MHz also shows a spectral flattening. A sample of ultra-steep spectrum (USS; $\alpha < -1.1$) radio sources is selected in the Boötes field from the spectral indices computed between 62 MHz, 153 MHz and 1.4 GHz, making use of the higher frequency data available in this field. These USS sources are likely to be associated with massive high redshift radio galaxies and the derived photometric redshifts show they are located in the $0.7 \lesssim z \lesssim 2.5$ range.

The first LOFAR, $130 - 169$ MHz, High Band Antenna (HBA) deep field observations of the Boötes field are presented in **Chapter 4**. The 19 square degree image, has a rms noise of $\sim 120 - 150\,\mu$Jy beam^{-1} and resolution of 5.6×7.4 arcsec, at least an order of magnitude deeper and $3 - 5$ times higher in resolution than that achieved with the GMRT observations in Chapter 1. Particular care is taken in the calibration of this data, making use of an advanced direction-dependent calibration scheme. The resulting radio source catalogue contains 5 652. Differential source counts which are an order of magnitude lower in flux density than previously done are presented. The counts show a flattening at a $\lesssim 10$ mJy with the rise of the low flux density star forming galaxies.

Chapter 5 is a study of the evolution of the fraction of radio-loud AGN as a function of their host stellar mass and shows how the fraction of low mass galaxies hosting high power radio-loud AGN increases with redshift. This is done by combining radio and optical data with one sample in the local universe, $0.01 < z \leqslant 0.3$, and a second sample at higher redshifts, $0.5 < z \leqslant 2$. An increase of more than an order of magnitude in the fraction of lower mass ($M_* < 10^{10.75}$ $M_\odot$) galaxies hosting radio-loud AGN is observed. On the other hand the fraction of high mass hosting radio-loud AGN remains more or less constant out to redshifts of 1–2. An increase in cold or radiative mode accretion with increasing cold gas supply at earlier epochs is responsible for the rising population of low mass radio-loud AGN.

In **Chapter 6** a further study of the redshift evolution of radio AGN as a function of the properties of their galaxy hosts is made. This uses the LOFAR data of the Boötes field from Chapter 3. The optical-infrared data is used to compile a catalogue of galaxies with photometric redshifts, stellar masses and rest-frame colours. We use this to study the host galaxies of high power $P_{1.4\,\mathrm{GHz}} > 10^{25}\,\mathrm{W\,Hz^{-1}}$ radio sources at intermediate redshifts, $0.5 \leqslant z < 2$. We also attempt to determine the mid-infrared AGN contribution to classify the radio-sources as HERGs and LERGs on the basis of photometry. We show that the fraction of HERGs and the fraction of blue radio AGN increases with redshift.

1.4 Future Prospects

The future is bright for radio AGN evolution studies. The current LOFAR surveys are already providing larger, higher redshift samples, such as those presented in this thesis. Soon, other continuum surveys to be performed with instruments such as APERTIF and the new JVLA will provide complementary higher frequency. Deeper photometric surveys are also currenty underway or in planning, including PanSTARRS. New multi-object survey spectrographs, such as WEAVE (Dalton et al. 2012) on the 4.2-m William Herschel Telescope (WHT), will provide much larger samples at high redshifts. WEAVE-LOFAR is a planned follow-up survey that will provide the primary source of spectroscopic information for the LOFAR surveys. In particular, WEAVE will provide spectra for $\approx 10^7$ objects at $z > 2$ using Ly_α emission over $10,000$ square degrees. Spectra are required for much more than simply estimating redshifts; they allow for the robust decomposition between star forming galaxies and AGN, and between accretion modes in the AGN. Spectra also permit the measurement of velocity dispersions, estimates of metallicities and virial black hole masses. For many galaxies metallicities and stellar velocity dispersions will provide further important information on the chemistry and dynamical mass of systems and their evolution, and the accretion mechanism for radio AGN can be determined, all crucial ingredients in galaxy formation and evolution models. Many thousands of WEAVE-LOFAR spectra will thus provide an important step forward in understanding the feedback processes in AGN.

Looking further ahead, the field is poised for another revolution, in terms of groundbreaking depth and area covered by future optical imaging and spectroscopic surveys (e.g. LSST, Euclid, 4MOST, MOONS). Finally, AGN and galaxy evolution studies also form an important part of the science case for the SKA (Kapinska et al. 2015).

1 Introduction

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