Facets of radio-loud AGN evolution : a LOFAR surveys perspective

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Summary

Active Galactic Nuclei

Active Galactic Nuclei (AGN) are powered by gas falling into 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 these AGN are diverse, from incredibly high luminosities, emission on very small scales, variability, broad and narrow emission lines, radio emission, to polarised emission. AGN play a crucial role in the evolution of galaxies and are necessary to produce the observed properties of galaxies in the contemporary Universe. 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. This feedback allows the central black holes to control or terminate star formation in their host galaxies. It is important then to understand the fueling mechanisms of AGN and their feedback processes and how these evolve over cosmic time.

Radio continuum observations are an important means to find AGN. 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 can be most directly observed and measured. The observed radio AGN population can be split in two categories, with the division between them based on their accretion rates (see Fig. 1). The populations are distinct in their SMBH and host galaxy properties. The first population is associated with radiatively efficient accretion via an accretion disc. These sources fit the paradigm of classic optical 'quasars', radiating across the electromagentic spectrum. This 'radiative mode' is characterised by strong optical emission lines and so are refered to as 'high-excitation' sources. High excitation radio galaxies (HERGs) are typically hosted by lower mass, bluer galaxies in less dense environments. This mode may be important in curtailing star formation at early times and creating the relationship between black hole and host galaxy masses that is observed in the nearby Universe. The second class of radio AGN was first noted by their lack of emission lines and are thought to occur when hot gas accretes directly onto the supermassive black hole in a radiatively inefficient manner. They lack any evidence of mid-infrared emission from dusty tori and accretion-related X-ray emission. These low excitation radio galaxies (LERGs) are hosted by galaxies that, in general, differ from those hosting HERGs: higher mass, redder and occurring in more dense environments. This 'jet 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. It may be responsible for maintaining present-day elliptical galaxies as 'old, red and dead'.

Low Frequency Radio Astronomy

The radio emission from AGN is synchrotron radiation, which is caused by relativistic electrons spiraling around magnetic field lines, both of which likely originate near the central SMBH. This

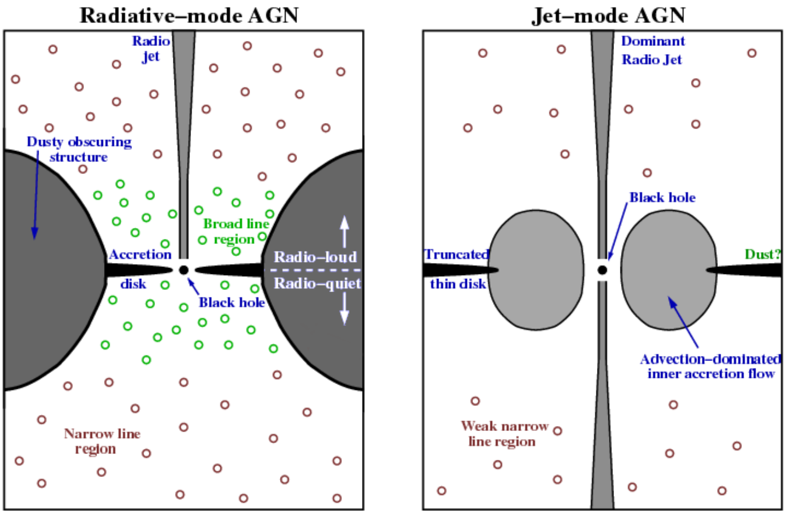

Figure 1: Schematic drawings of the central engines of AGN in the radiative mode (*left*) and jet mode (*right*). Radiative-mode AGN have a thin accretion disk that illuminates the broad- and narrow-line regions with UV radiation. At some viewing angles, a dusty, obscuring structure may inhibit the view of the accretion disk and broad-line region. While at other angles, these features are visible. A small fraction of these sources produce powerful radio jets. Jet-mode AGN lack the accretion disk and emission lines, but do have radio jets. (Image reproduced from Heckman & Best 2014).

emission has a characteristic power-law spectral shape, $S_\nu \propto \nu^\alpha$ over decades in frequency, where the spectral index, α, is typical negative. Radio observations of AGN can thus benefit from the increased brightness towards lower observing frequencies. 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), as well as a return to lower frquencies. In particular, the Low Frequency Array (LOFAR, see Fig. 2) 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 joined electronically to imitate a dish. The array is composed of several 'stations' each containing a number of simple dipoles. LOFAR operates within the very high frequency (VHF) band that is commonly used for FM radio and television broadcasting, amateur radio, and marine and air traffic communications. 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 array alone provides radio images of the sky with unprecedented resolution and sensitivity at these frequencies and allows large areas of the sky to be surveyed. The inclusion of the international stations allows for images of individual sources with resolutions a factor ten higher.

These telescopes bring both new scientific and new technical challenges. These challenges include developing new theories to describe instrumental and atmospheric 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 contrast. 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. In particular for low frequency ra-

Figure 2: 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).

dio astronomy it is increasingly important to perform direction-dependent calibration, which corrects for the distorting effects of the ionosphere.

This Thesis

One of the most fundamental issues in understanding the role of AGN in galaxy formation is the need to accurately measure the accretion history of black holes, and to compare this with the growth of stars in galaxies: do black holes and their host galaxies grow coevally, or does one precede the other? Most of the growth of SMBHs and the stars in galaxies occured when the Universe was between 3 and 8 billion years old. Their present day growth is an order of magnitude lower than it was at that 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 optical surveys have greatly increased our understanding of the contemporary population of AGN. 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 distant times. To this end, this thesis aims to answer the following:

1. How does the relationship between galaxy mass and radio AGN fraction, i.e. the radio source duty cycle, evolve over time?
2. How does the radio AGN population evolve over time?
3. What is relationship between host galaxy properties and radio AGN in the earlier Universe?

The main tool for these studies is deep, high-resolution, low frequency radio imaging of fields with excellent complementary data. The first part of this thesis (Chapters 2 to 4) uses the most advanced calibration techniques to provide low-frequency radio images using the GMRT and

LOFAR. The latter part of the thesis (Chapters 5 and 6) combine radio samples with optical data to study host galaxy properties of radio-loud AGN over cosmic time.

Chapter 2 presents 153 MHz GMRT observations of the NOAO Boötes field. 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 software package. The GMRT mosaic image, which combines seven observations, provides the largest and deepest low frequency image at the time. An important simple diagnostic of the radio source popoluation is the number of sources of different brightnes, or 'source counts'. The 1289 radio sources in the GMRT image were used to derive the low frequncy source counts.

In **Chapter 3** the first LOFAR LBA observations of the Boötes and 3C 295 fields at 34, 46, and 62 MHz are presented. The images are the deepest ever obtained in this frequency range and each image contains 300–400 radio sources. Source counts are again derived each frequency. The lowest frequency source counts show that the average spectral index of radio sources flattens towards lower frequencies, i.e. radio sources are not as bright as expected at lower frequencies. A sample of ultra-steep spectrum (USS) radio sources is selected in the Boötes field from the spectral indices computed between 62 MHz, 153 MHz and 1.4 GHz. These USS sources are of interest because they are likely to be associated with massive distant radio galaxies.

The first LOFAR, 130 – 169 MHz, HBA deep field observations of the Boötes field are presented in **Chapter 4**. The 19 square degree image is an order of magnitude more sensitive and four times higher in resolution than that achieved with the GMRT observations in Chapter 2. 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 sources. The source counts are are an order of magnitude lower in flux density than previously done at these frequencies. The counts show a flattening for the faintest sources, which is connected with the rise of the faint 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 cosmic time. This is done by combining radio and optical data for one sample in the local universe, and a second more distant sample. An increase of more than an order of magnitude in the fraction of lower mass galaxies hosting radio-loud AGN is observed in the distant sample. On the other hand the fraction of high mass galaxies hosting radio-loud AGN remains more or less constant. An increase in cold or radiative mode accretion with increasing cold gas supply at earlier cosmic time is argued to be 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 4 combined with optical and infrared data. The optical-infrared data is used to compile a catalogue of galaxies with distances, stellar masses and intrinsic colours. We use this to study the host galaxies of strong distant radio sources. 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.

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 new and upgraded instruments will provide complementary higher frequency. Deeper photometric surveys are also currenty underway or in planning. In particular, new optical instruments, will provide much larger samples of galaxies at high redshifts for the radio sources identified in the LOFAR surveys. 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. Finally, AGN and galaxy evolution studies are also an important part of the science case for the SKA, the next step forward in radio astronomy.