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English Summary

Active Galaxies

At the heart of almost every massive galaxy resides a black hole that is millions to billions times more massive than the sun. Most galaxies are host to dormant black holes. In a fraction of galaxies, the black holes are observed to interact with their host galaxies, as they draw in and accumulate gas into a bright, hot disk of material that swirls around them like water around a drain in a bathtub. When the black hole of a galaxy is being fed in such a manner, the galaxy is called an 'active galaxy.' The disk of accumulating material around a black hole is tiny when compared to the size of the entire galaxy, but can produce enough optical light to outshine the light from the rest of the galaxy. This bright light coming from a very compact disk appears as a point-like source, comparable to a star, to an observer on Earth, leading to the name quasi-stellar or *quasar*. Active galaxies have a variety of different characteristics, and not all of them are quasars. The disk of accumulating material can be surrounded by dusty molecular gas. This dusty gas becomes warmer as it absorbs the light from the disk, which makes it glow bright in the infrared. Since everything on the sky is seen in two rather than three dimensions, sometimes the orientation of a galaxy means the dusty gas will block the light of the disk, and while we know the galaxy is an active galaxy, a quasar is not observed. There are other observational characteristics that will also depend on orientation, and astronomers use a wide variety of clues to identify active galaxies. Figure 1.3 shows a diagram of the region around the black hole in a radio loud active galaxy.

Radio Galaxies

About 10 per cent of active galaxies also produce jets of plasma moving at relativistic speeds. These jets produce radio emission from electrons circling in magnetic fields, a process called synchrotron radiation. These bright, powerful jets comprise two classes with distinct morphological features. Figure 2 shows

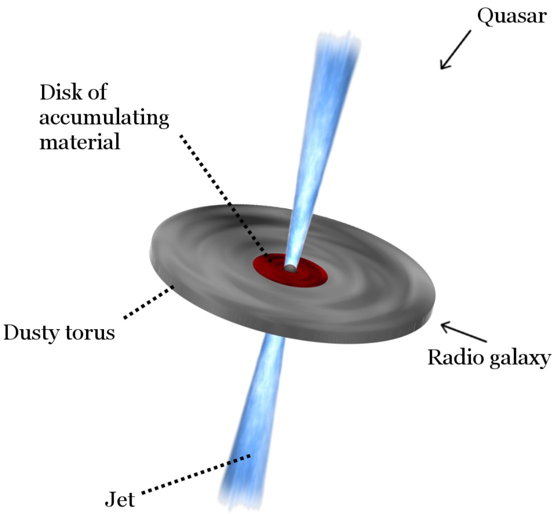

Figure 1: A diagram of the black hole and surrounding region in an active galaxy. The jet is only present in about 10 per cent of active galaxies, which are termed 'radio-loud'. Active galaxies can exhibit different observed features based on its orientation with respect to the observer, and the arrows indicate the type of object that is seen based on viewing angle. Image credit J. Harwood.

examples of the two different classes: Fanaroff-Riley I (FR I) sources which have radio jets that are more like fountains, with wider jets that are dimmer towards their edges; and Fanaroff-Riley II (FR II) sources, which have highly directional radio jets that are brightest where the jets terminate.

Distant radio galaxies are thought to evolve into the most massive galaxies in the present day Universe, and often the space around them has more galaxies than expected. They are therefore important beacons for studying galaxy evolution, as populations of galaxies can be studied as they traverse into clusters of galaxies, which are the largest gravitationally bound objects in the Universe. The more distant radio galaxies exhibit different characteristics to local radio galaxies, and it is not understood if these differences are intrinsic or environmental. One of the most intriguing differences between local and distant radio galaxies is that the more distant a radio galaxy is, the steeper its radio spectrum is (the steepness is measured by the spectral index parameter, α). The relation between radio spectral index and redshift (an astronomical distance measurement) has been successfully exploited in the past to find some of the most distant galaxies. However the cause of the relation still remains unknown.

Carbon Radio Recombination Lines

The cycle of star formation plays a key part in shaping a galaxy's evolution. The interstellar medium (ISM) provides the fuel to make new stars and is the reposi-

Figure 2: Examples of typical Fanaroff-Riley FR I and FR II sources. *Left:* FR I radio galaxy Centaurus A. The color purple shows the radio emission (Credit: X-ray: NASA/CXC/CfA/R.Kraft et al; Radio: NSF/VLA/Univ.Hertfordshire/M.Hardcastle; Optical: ESO/WFI/M.Rejkuba et al.). *Right:* Cygnus A, the archetypal FR II radio galaxy. The color red shows the edge-brightened radio emission. (Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Radio: NSF/NRAO/AUI/VLA).

tory for the ejecta of old stars. There are many different components of the ISM, and understanding how all of these components contribute to star formation is critical to understanding galaxy evolution. One of the least known components of the ISM is the cold neutral medium, which is over 10^{19} times less dense than air on Earth, and a couple hundred degrees below 0 degrees Celsius. This nebulous gas consists mostly of neutral hydrogen atoms, and carbon atoms that are singly ionised (that is, they are missing an electron).

Carbon atoms normally have six protons and six electrons and are about half a million times smaller than the average thickness of a human hair. The outermost electron is easily bumped out of orbit by low-level ultraviolet radiation, leaving behind a singly-ionised carbon atom. In the cold neutral medium, these carbon ions co-exist with free electrons and neutral hydrogen atoms. The free electrons can be re-captured by the carbon ions in a process called recombination (see Figure 3 for a depiction). When the recombination happens to a high energy level ($n \geq 300$), the process produces spectral features at low radio frequencies (≤ 240 MHz). There are many of these carbon radio recombination lines (CRRLs) in the radio frequency range, but they are strongest below the FM radio band.

Observing CRRLs at low frequencies has three main advantages. First, they are easier to detect because the physical processes involved increase their

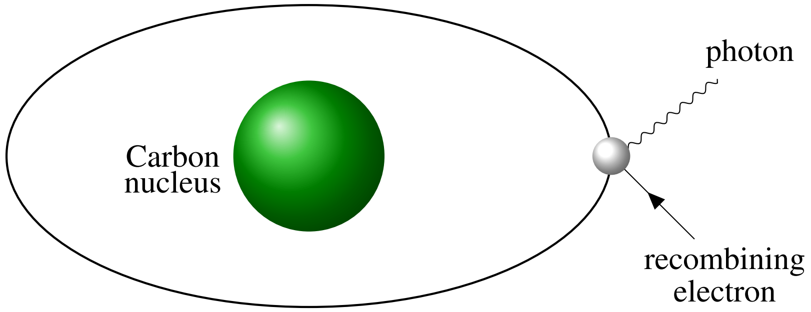

Figure 3: A depiction of a recombining carbon atom. The green ball represents the nucleus, which includes protons, neutrons, and five electrons. The white ball represents a free electron which has been captured by the carbon nucleus, a process which emits a photon.

strength. Second, the lines are closer together in frequency at lower frequencies, and instruments with wide bandwidths can observe multiple CRRLs simultaneously. Considering multiple CRRLs simultaneously will increase the signal to noise ratio, providing better data with which to observe the cold neutral medium. Third, low-frequency CRRLs are seen as absorption features (rather than emission features), and detections are limited only by the amount of absorbing gas present and not the distance to the gas. This opens up the possibility of observing CRRLs at very large distances, where virtually nothing is known about the cold neutral medium content of galaxies.

By comparing observations of these carbon radio recombination lines to detailed theoretical models it is possible to gather information on the temperature and density of the cold neutral medium. These models were developed in the 1960's and 1970's and have only recently been expanded to include the lowest observable radio frequencies (Salgado et al., submitted). Advances in computing have also allowed for more accurate computation of the necessary quantities to calculate the electron population in carbon atoms, as well as a complete treatment of how the stimulation of the ground state of carbon can impact the strength of CRRLs.

The Low Frequency Array

The resolution a telescope can achieve is related to the observed frequencies, and the size of the telescope. High resolution at low frequencies requires telescopes so large that they are impractical, and radio astronomers often use arrays of telescopes. Combining the signals from individual telescopes effectively creates an instrument with the desired properties of a much larger telescope. This is a process called interferometry.

The Low Frequency Array (LOFAR; van Haarlem et al., 2013) is a new radio interferometer with a revolutionary phased-array design that makes use of electronically pointed dipoles rather than traditional dish telescopes. The simple dipole antennas are grouped into stations. There are 37 stations concentrated in the Netherlands, and 12 stations spread across five other European countries. There are two different types of dipoles in each station. The High Band Array (HBA) operates just above the FM radio band and consists of thin metal dipoles supported by Styrofoam and protected from the weather. The Low Band Array (LBA), which is the focus of this thesis, operates just below the FM radio band and is most sensitive around 60 MHz. Each LBA antenna consists of two simple wire dipoles attached to the ground and supported at their apex in the center by a plastic pipe. The station locations are shown in Figure 4, along with a bird's eye view of a station, and a close up of the LBA dipoles.

Most LOFAR observations use only the stations in the Netherlands, which provide fields of view 40 times larger than the full moon, and the smallest object that can be resolved is about the size of Mars in the night sky. The wide geographic distribution of international stations provides LOFAR with an effective collecting area more than a thousand kilometres across, allowing resolutions ten times better to be achieved. This is equivalent to the size of a US penny or 10 euro cent coin that is 8 kilometres (5 miles) away. This capability sets LOFAR uniquely apart from other low-frequency arrays, and enables exploration of entirely different science topics.

With new technological advances come new challenges. Low frequency radio telescopes operate in a frequency range where the ionosphere can have a large impact on observations, causing stationary radio sources to appear to move and/or scintillate in an image, just like stars seem to twinkle when seen with the naked eye through turbulent atmosphere. New calibration techniques are necessary to remove this effect from the radio data, and the problem is even more challenging when using the full International LOFAR, as it is challenging to combine signals from geographically isolated stations. Errors in station positions, different station clocks, and errors from propagation through different atmospheric conditions must all be accounted for.

Figure 4: *Top:* The locations of LOFAR stations. The data in this thesis were taken before the stations in Poland were constructed, when the longest baseline was between Onsala and Nançay (1292 km). *Middle:* The LOFAR-UK station at Chilbolton. The LBA antennas are in the foreground with the HBA antennas clustered together under a weather-protective covering behind the LBA. *Bottom:* Dipoles from an LBA station within the central core of LOFAR, with the author in the picture for scale.

This Thesis

The goal of this thesis is to use low frequency radio astronomy tools to help answer the following questions:

- Are more distant radio galaxies fundamentally different objects than their nearby counterparts?
- What causes the correlation between radio galaxy spectral index and distance?
- What is the cold gas content in radio galaxies, and how does it play a part in the cycle of star formation?

In particular, this thesis uses several tools to help answer these questions: (i) catalogues of sources from LOFAR images that detect fainter galaxies than ever before detected at low frequencies; (ii) images with the highest resolution at frequencies below 100 MHz using the International LOFAR LBA stations; and (iii) observations of spectral features from both LOFAR and the Karl G. Jansky VLA (VLA).

Chapter 2 investigates whether the projected sizes of radio sources support other evidence that the orientation of an active galaxy on the sky directly informs the observed characteristics (the other alternative is that objects with different characteristics are intrinsically different). The viewing angle dictates whether the observer sees the obscuring torus edge on (radio galaxy) or is able to see the disk of accumulating material inside the torus (quasar). Using data from a catalogue of LOFAR-detected radio sources from Williams et al. (2016) we find that the radio galaxies are on average 3.1 ± 1.0 times larger than the quasars for the LOFAR-detected radio sources, which is evidence for orientation-based unification.

Chapter 3 is a detailed study at 55 MHz of 4C 43.15, one of a sample of 10 distant FR II radio galaxies. This chapter presents the highest resolution images below 100 MHz, using the International LOFAR. The images of this radio galaxy reveal a bridge of radio emissions between the two FR II radio lobes, the first time this has been seen in a distant radio galaxy. The observed properties of 4C 43.15 are similar to those seen in local radio galaxies, including the rest-frame radio spectral index. This implies that distant radio galaxies are fundamentally the same as their local counterparts.

Chapter 4 investigates whether the relation between spectral index and redshift ($\alpha - z$) can arise simply due to increased energy losses at higher frequencies in the overall radio spectrum due to the proximity of the cosmic microwave background (CMB), which increases as $(1+z)^4$. This chapter uses a new approach of selecting archival data for ~50 local radio galaxies with enough data available to model their entire radio spectra, and using these to simulate radio spectra of radio galaxies at higher redshifts. We find that the observed relation can be entirely reproduced with only the increased synchrotron losses due to inverse Compton scattering of photons from the CMB at high redshift, without having to invoke any intrinsic α-power relationship or environmental effects.

Chapter 5 presents the first detection of CRRLs in a galaxy other than our own. This galaxy is nearby M82, which is undergoing an intense, short-lived period of star formation. This is the first extragalactic detection of RRLs from a species other than hydrogen, and below 1 GHz. The low frequency CRRLs come from carbon atoms that are present in the heart of M82 and trace the cold neutral medium. By stacking 22 CRRLs in the frequency range of 48-64 MHz, corresponding to energy levels (quantum levels) of $n = 468 - 508$, an 8.5σ detection was achieved. Recombination to such high levels mean that the Carbon atoms are about 2.1 microns in size. The line profile appears to be correlated with cold atomic gas in the nuclear region of M82, confirming what is expected from observations of CRRLs in the Milky Way.

Chapter 6 builds on Chapter 5, as the CRRL detection described therein does not provide enough data to compare with the detailed models to constrain the gas temperature and density. Using VLA observations at a higher frequency range (250−480 MHz) we stacked 12 CRRLs to find a meaningful upper limit with which to constrain the gas temperature and density by comparison with models. We find that the gas temperature and density are consistent with Galactic values for the cold neutral medium.

Chapter 7 describes the calculation of bound-bound Gaunt factors for levels up to $n = 2000$. These factors are used to calculate oscillator strengths, one of the necessary quantities in the updated theoretical models of CRRLs (Salgado et al., 2016a,b). A review is presented of various calculation methods, with particular attention given to the computational problems that led previous authors to use approximations with large errors. The new calculations have improve the errors by more than a factor of 10. The values are useful for a wide range of physical applications, and are tabulated and published online.

Overall, this thesis has two major conclusions:

- Distant radio galaxies look like their local counterparts
- Carbon radio recombination lines are detectable in extragalactic sources and can be powerful tools for measuring the properties of the cold neutral medium in distant galaxies