AGN and their radio relics

The first celestial radio emission was registered by Karl Jansky, an engineer working for the Bell Laboratories (owned by AT&T) in the fourth decade of the last century. He noticed that the source of a persistent noise affecting wireless communications was the center of the Galaxy (Figure 1). About a decade later, Grote Reber made maps of the Galaxy and some other radio sources on the sky using a radio telescope that he built himself. Radio astronomy was born.

Over the decades that followed, radio astronomy has made huge advancements, uncovering a whole new range of phenomena which became observable only at radio frequencies.

Gigantic lobes of radio radiation were observed at either side of elliptical galaxies. As the resolving power of radio telescopes increased, these were found to be sometimes connected to the cores of their host galaxies by thin jets of radio emission.

Later, a different class of intriguing sources were found - bright quasi stellar objects displaying very unusual optical spectra having unknown emission and absorption lines. In the 60’s, in a flash of insight, astronomer Maarten Schmidt has deduced that the spectra were pointing to the fact that these objects were very, very distant, on average being billions of light years away. The fact that they are so bright and star-like (they were named quasi stellar objects, QSOs or quasars in short) means that the large amounts of energy they radiate originate in a relatively small volume.

After considering a few theoretical mechanisms which could account for such energetic processes, over time an understanding has emerged that the only candidate process is accretion of matter onto a compact object. The observed physical parameters pointed towards a super massive black hole (SMBH) being the central object, with a mass in
the range of millions to billions of solar masses. Infalling matter forms an accretion disk which radiates over all of the electromagnetic (EM) spectrum. Further out, the disk may expand into a torus; at right angles to the disk, the magnetic fields present in the SMBH / disk may collimate a jet of highly relativistic particles which radiate non-thermal, synchrotron radiation. These jets remain coherent for huge distances, pushing through the interstellar medium (ISM) of the host galaxy and producing the radio emission regions observed (see Figure 2 for an image of the radio galaxy HerA). This phenomenon is one of the most spectacular manifestations of an Active Galactic Nucleus (AGN).

Soon (in the 80’s) it was realized that AGN could be the phenomenon behind radio galaxies, quasars and other similar sources. AGN come in many flavors; this diversity is mostly due to orientation effects and unification schemes were proposed to explain how what we observe relates to the AGN concept. When our line of sight views an AGN down the rotation axis of the SMBH or with a slight offset we observe a point-like optical source. If the AGN does not produce radio emission, we can observe an optical QSO, or a type 1 or 2 (if looking almost at right angles to the rotation axis) Seyfert galaxy. In the case where the AGN is also a radio source, we observe a quasar accompanied with strong (highly relativistically beamed) radio emission mostly coming from the radio jet when we view the AGN almost in the direction of the rotation axis. If we look at the
Figure 2: A composite image of the brightest radio source in the constellation of Hercules. HST’s Wide Field Camera 3 provides the optical image, while the radio map (purple) is obtained by the Karl Jansky VLA radio telescope. We can see the radio jets emanating from the AGN hosted by the elliptical galaxy which is a 1000 times more massive than our milky way galaxy. The radio jets feed the radio emitting lobes; we can see flickers in the AGN activity reflected in multiple bubbles of plasma in the right side jet, while the opposite jet shows a helical structure. (© NASA, ESA, S. Baum and C. O’Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA))

AGN at a high angle to the rotation axis, the central engine is hidden from view, and the radio emission is the most prominent feature - we observe a radio galaxy. Imaging the host galaxies of some quasars (especially since the launch of the Hubble Space Telescope; HST) contributed towards strengthening this point of view.

Studying AGN is an entire sub-field in astronomy. Much has been ascertained in the past few decades about their energetics, spectral properties and their interaction with the surroundings. At the same time, much remains a mystery. AGN radiate over the entirety of the EM spectrum and span a staggering range of spatial scales; their SMBH engine is comparable to the extent of our solar system, yet their jets and radio lobes can span millions of light years. Consequently, studying them requires observations with a variety of instruments and requires an understanding of processes involving quantum theory, general relativity, galaxy evolution and even cosmology, basically the entirety of modern astronomy.
In the present study we concern ourselves with studying AGN in the radio part of the EM spectrum. AGN in the radio can be variable objects, showing fluctuations in brightness at timescales from days to years. Using radio interferometry (connecting multiple telescopes and thus obtaining an instrument with larger sensitivity and resolving power) we can study AGN emission on varying spatial scales. Variability is most noticeable in the radio cores of AGN. The larger scale morphology of radio galaxies, the radio lobes, record the variability of AGN activity on much longer time scales.

The SMBH can exhaust its supply of accreting matter and once that happens, the AGN shuts down and becomes inactive. The optical emission stops, the radio jets vanish. Consequently, after a time delay long enough for the information of the shutdown to be transmitted to the extended lobes, the supply of accelerated particles to the radio lobes ceases. The lobes start to fade, i.e. their radio brightness diminishes. However, the magnitude by which the radio lobe brightness decreases is different at different radio wavelengths. Thus, observing the fading radio lobes across the radio spectrum is a necessary step in inferring the activity history of an AGN.

The theoretical basis for describing non-thermal (synchrotron) radio emission was given in the 60’s by Vitaly Ginzburg and Nikolai Kardashev. Later, it was expanded upon by many other astrophysicists. Comparing theoretical models of radio source spectra to observations can help us estimate the period of time an AGN has spent in an active phase and the time interval that has passed since its shutdown. Radio relics thus become very important; they are the only observational tracer of past AGN activity episodes.

These relic structures are brightest at low radio frequencies. We have a powerful new tool to aid us in their discovery and characterization. The LOw Frequency ARray (LOFAR) telescope (Figure 3) is a radio interferometer working in the frequency ranges of 20 MHz - 80 MHz and 120 MHz - 240 MHz. Its antennas are clustered in groups called stations. Most of these stations are spread across the northern parts of the Netherlands, with some extending out to Germany, the UK, Poland and Sweden. In a single exposure, LOFAR can image a patch of the sky 5° across (as large as 10 full Moons arranged side by side) which facilitates discovery.

**This thesis**

We have studied various AGN relics and for some of them we have determined their spectral properties, leading to an estimate of the age of the AGN that have powered them.

Chapter 2 describes the properties of a relic we have discovered observing at a frequency of 1400 MHz using the Westerbork Synthesis Array Telescope (WSRT) located in northern Netherlands. The region of relic emission is located around a currently active AGN which is classified as a compact steep spectrum (CSS) radio source. The surface brightness of the relic is very low. Spectral index and ageing studies will enable us to determine the duty cycle of the host AGN. The host elliptical galaxy is rich in cold gas (there is a vast ring of neutral hydrogen gas around it) which may provide the fuel for the AGN activity.

AGNs can be hosted by galaxies in more complex environments, such as galaxy clusters. In Chapter 3 we have studied a relic produced by such an AGN. Its morphology and age are defined by its environment. We have studied in detail its radio radiation at different frequencies, spanning from 61 MHz (LOFAR, see Figure 4) to 4800 MHz (using
the Very Large Array - VLA interferometer located near Socorro, New Mexico - USA). We have found that the radio source (catalogued as 4C 35.06) is a combination of an old relic and a re-started phase of AGN activity. We have also used the WSRT to search for cold gas (traced by H$\text{I}$) and found cold gas connected to the host galaxy of the AGN.

Another AGN relic in a galaxy cluster was studied in Chapter 4, located at a larger distance ($z = 0.159$). Using LOFAR data as well as VLA imaging and images from the Giant Meterwave Radio Telescope (GMRT, located near Pune in India) we have determined that the AGN which created the now relic emission has shut down around 60 million years ago. In the same source, we have detected another radio component which is most likely an older plasma bubble compressed by a shock wave generated by the merger of two galaxy clusters (the brightest galaxy in one of them is the host galaxy of our AGN).

AGN relics are also found in galaxies which are not part of a cluster. We have analyzed such a relic in Chapter 5, and we have found that the AGN has stopped its activity more than 100 million years ago. However, sections of the radio lobes which were replenished by the radio jet are just 20 million years old.

In this thesis, we have shown the usefulness of LOFAR to detect relic emission at low frequencies, at a spatial resolution comparable to that obtained at much higher frequencies. This has enabled us to do matched comparisons of multi-frequency maps.

Figure 3: The six stations comprising the very core of the LOFAR telescope, the so called super-terp imaged on May 23, 2010 (© Top-Foto, Assen).
Figure 4: **Left:** LOFAR 61 MHz radio image (red) overlaid onto an optical image of the AGN host galaxy of the radio source 4C 35.06. **Right:** LOFAR 140 MHz image (red, yellow) overlaid onto an optical image of the AGN host galaxy of the B2 0924+30 radio source.

The usefulness of LOFAR as a survey instrument is showcased in Chapter 6 where we have performed a search for AGN radio relics in the first LOFAR sky survey, the Multi-frequency Snapshot Sky Survey (MSSS). While having a limited resolution and sensitivity, it is a valuable proof of concept. We have been able to put limits on the prevalence of relics around compact radio sources.

In Chapter 7, we have studied in detail the low frequency properties of two giant radio galaxies (3C 236 and NGC 6251). This was done for the first time at the relatively high resolution of about 1’ at around 140 MHz. We have been able to image previously undetected radio emission regions in the radio lobes of NGC 6251 (Figure 5).

Our research shows the potential of LOFAR and is the first attempt at using LOFAR observations in the studies of AGN radio relics. We have found that low frequency observations are necessary to provide constraints to models and are essential for proper interpretation of the obtained results. We have also uncovered new potential relic sources, thus demonstrating the survey capabilities of LOFAR. The future is bright at low frequencies.
Figure 5: LOFAR image of the giant radio galaxy NGC 6251 at 140 MHz.