The role of neutral hydrogen in the life of galaxies and AGN

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Chapter 1

Introduction

1.1 A short history of H I observations

We happen to live in a galaxy called the Milky Way. The name arose due to the fortunate fact that human beings are endowed with rich imagination, which has got people thinking about the wonders of the sky for thousands of years. Galileo Galilei was the first one to use, and point an optical telescope on the Milky Way. It probably disappointed a lot of people that instead of seeing highly resolved dairy products, he found himself staring at billions of stars. The Milky Way appears to cross the sky as a bright line because we are living inside this flat galaxy, about 8 kpc distance away from the Galactic center (see Fig. 1.1). The central part of the galaxy is obscured by interstellar dust, hence our knowledge of the detailed structure of the Milky Way has remained limited for a long time. Due to a great discovery of the 20th century, this has changed for good, and galaxies literally appeared in a whole new light.

Each chemical element, including H I, emits and absorbs radiation at one specific frequency. It was predicted by Dutch astronomer Henk van de Hulst that atomic hydrogen (H I) would emit electromagnetic radiation at the frequency of 1420.405 MHz due to a change in the energy state of the hydrogen atom. This frequency falls in the radio regime of the electromagnetic spectrum. Shortly after the spectral line of neutral hydrogen was first detected in 1951 by Ewen and Purcell at Harvard University, the first maps of neutral hydrogen of our galaxy were created by van de Hulst in collaboration with Jan Oort and Lex Muller. For the first time, the H I maps revealed the spiral structure of the Milky Way (see Fig. 1.1). Later, linked telescope arrays, radio interferometers have been built, allowing astronomers to study the H I gas in extragalactic sources at high resolution.

The main difference between optical and radio telescopes is that while in optical one can measure the number of received photons, radio telescopes detect electromagnetic waves. The technology of radio interferometry was developed by British and Australian engineers and radio astronomers, including Ruby Payne-Scott, the first female radio astronomer. Taking advantage of the reflective surface of the sea, they converted a single radar antenna into a sea-cliff interferometer near Sydney, Australia. In this simple configuration, the radio detector was placed on top of a cliff, measuring the interference pattern of radio waves reflected off the water surface.

Figure 1.1: On the left: Artistic view of the Milky Way. On the right: early-type galaxy, randomly selected from the sample discussed in this thesis

How do radio interferometers work?
The u-v plane is the projection of the baselines i.e., spacings between antenna-pairs, in wavelengths (with respect to the central frequency). A two-element interferometer measures the amplitude and phase of one spatial frequency (one point in the u-v plane). The entire interferometer measures the complex visibilities at a series of different frequencies that can be Fourier-transformed to create the brightness distribution of the sky. Continuum images of the brightness distribution are created by averaging the flux measured in each frequency channel. Furthermore, by removing the continuum emission, one can create the H I spectral line cube of the observed volume of the sky. In the case of line observations, every frequency channel will provide one H I image that will form the data cube.

Due to the fact that we are living in an expanding Universe, the frequencies emitted by chemical elements from within distant galaxies appear redshifted toward lower frequencies compared to the rest frame. According to Hubble's law, the redshift is approximately proportional to the distance of the galaxies. Hence, the spectroscopic redshift can serve as a rather accurate distance (or lookback time) measurement for the galaxies. To be able to detect H I in galaxies from the nearby to the distant Universe, radio telescopes need to observe a large range of frequencies. This has become possible thanks to improvements achieved in radio astronomy. Wide-band observations with telescopes like the Westerbork Synthesis Radio Telescope (WSRT), the Karl G. Jansky Very Large Array (VLA), the Australia Telescope Compact Array (ATCA), and many more facilities that are mentioned in this thesis, made it possible to observe large volumes of the sky in H I up to relatively high redshift.

H I observations has lead to important discoveries over the years. Hydrogen is the most abundant gas in the Universe, and it provides the primordial gas from which stars eventually form. For example, in the disk of the Milky Way about 70% of the gas is in atomic form. We have learnt that galaxies can have billions of solar masses ($M_\odot$) of

H I gas, sometimes extending way beyond the stellar disk of galaxies. Star formation is related with the presence of gas, as stars are born in 'stellar nurseries' of dense molecular hydrogen clouds. Neutral hydrogen is also a great tracer of how interactions and merging events disrupt or construct galaxies in the Universe. Furthermore, observations suggest that H I could be partly responsible for the triggering of one of the most energetic phenomena in the Universe, by feeding supermassive black holes in the centres of galaxies.

The signal emitted by distant sources is weaker, and H I observations in the higher redshift Universe are limited by the sensitivity of current telescopes. The next generation of radio telescopes, e.g., Apertif (Oosterloo et al. 2010b), the Australian Square Kilometre Array Pathfinder (ASKAP, DeBoer et al. 2009), MeerKat (Booth et al. 2009) and later on the Square Kilometre Array (SKA) are expected to bring H I studies to large, cosmologically significant distances. Building these facilities requires a great amount of work, financial support, and time, and it will take a few more years until they become fully operational.

However, in recent years also statistical methods have become available to push the detection limit of current radio telescopes, allowing one to to make full use of broad-band receivers and to extend H I observations to relatively high redshift. H I stacking has been used effectively to study, globally, the average H I content of large galaxy samples.

With the goal of studying large samples of faraway galaxies statistically, the work presented in this thesis uses spectral stacking analysis of H I. Using stacking techniques, we investigate the H I properties of hundreds of galaxies to get a better understanding of the role of H I in the evolution of galaxies over the past 1.5 Gyr. We also look at the gas properties of accreting supermassive black holes, i.e. active galactic nuclei (AGN), to investigate the interplay between AGN activity and the surrounding gas.

1.2 H I gas properties of galaxies

Almost a century ago, by looking at the photographic images of 400 extra-galactic nebulae, Hubble (1926) found that galaxies can be separated into two main types based on their morphological appearance: spiral galaxies and ellipticals. Spirals, also known as late-type galaxies, are rotating systems with bright stellar disks, while in galaxies which have spherical or elliptical shapes (early-type galaxies), the dynamics of stars is more chaotic. The two types of galaxies are presented in Fig. 1.1.

The morphological separation formed the basis of galaxy classification, and later these two main galaxy types were found to follow systematic trends in many properties. The colors and luminosities of galaxies have long been know to correlate with galaxy morphology (de Vaucouleurs 1961; Chester & Roberts 1964). Late-type spirals are typically blue with lower surface brightness, early-type galaxies are predominantly red and more luminous. These observational properties are easy to interpret in the context of star formation and stellar evolution history. Spiral galaxies are actively forming stars, hence their blue colors are given by young stellar populations. Early-type galaxies are typically non-star-forming, with older and redder stellar populations.

The interstellar medium of galaxies is not empty. Besides stars, galaxies can also contain gas and dust. Although the amount of the interstellar matter is usually only a small fraction of the total galaxy mass, the content and physical conditions of the interstellar medium are of great importance, as the formation of new stars will continuously affect the evolution and appearance of galaxies. Thanks to 21 cm observations of H I, early studies have shown that spiral galaxies almost always contain relatively large amounts of H I, while early-type galaxies contain very little, if any, gas (Roberts 1972). Hence early-type galaxies seemed to be typically 'red and dead' systems.

Later, through systematic H I studies of larger samples of galaxies, we have learnt that early-type galaxies are way more interesting than simple red and dead galaxies. In fact this group shows very complex H I properties. In recent years, the SAURON (Morganti et al. 2006; Oosterloo et al. 2010a), and ATLAS^{3D} (Serra et al. 2012) studies have carried out detailed analysis of the H I properties of early-type galaxies in the nearby Virgo cluster. These studies have shown that many early-type galaxies contain fast rotating stellar systems, and cold gas is present in a high fraction (about 40%) of early-type galaxies outside of the cluster environment. H I is in a settled disk/ring structure in about half of the detected cases. However the frequent presence of unsettled gas and tidal tails suggests that interactions play a prime role in affecting the gas content. In spiral galaxies the H I mass is known to correlate well with the optical diameter and luminosity of the disk (Haynes & Giovanelli 1984; Toribio et al. 2011); however, in early-type galaxies no such relation is seen. In fact, H I in early-type galaxies covers a broad range of H I masses and column densities, and along with the fact that the H I disk is often kinematically misaligned with respect to the stellar disk, these are strong indications that H I gas in early type galaxies is of external origin. In about 70% of galaxies which have H I gas in their central regions, also signs of on-going star formation are seen. This means that even though it is a modest effect, gas accretion and subsequent star formation do play role in the evolution of early type galaxies until the present days.

The mentioned studies have been carried out using direct observations in the nearby Universe. However, in order to understand the full picture of galaxy evolution, it is important to extend H I observations to larger distances.

Why is it important to push the redshift limit of H I observations?
Semi-analytic modelling of galaxy formation predicts that the cosmic density of H I remains constant as a function of redshift (Obreschkow & Rawlings 2009; Lagos et al. 2011; Popping et al. 2013). This is an intriguing result given that the star formation rate (SFR) displays a dramatic evolution, decreasing since $z \sim 2$ (Madau et al. 1996; Hopkins & Beacom 2006). In the local Universe one can use direct observations to constrain the cosmic H I mass density ($\Omega_{\rm HI}$) of neutral hydrogen (Zwaan et al. 2005; Martin et al. 2010). At higher redshift, because the sensitivity of H I emission observations is limited, observational constraints on the cosmic H I mass density are provided by Damped Lyman-alpha (DLA) measurments from the absorption spectra of background quasars (Rao et al. 2006; Prochaska & Wolfe 2009), or by statistical methods such as intensity mapping analysis (Chang et al. 2010), and H I stacking of emission spectra (Lah et al. 2007; Delhaize et al. 2013). The overall product of these studies reveals a modest evolution of the global H I content as function of redshift (see Fig. 8 of Delhaize et al. 2013), however, the increase is not significant up to $z \sim 0.1$.

1.3 Stacking of H I spectra

H I stacking is the process of co-adding the spectra of individual galaxies, with the goal of recovering the average H I signal in the stacked sample. During the stacking process, the spectra of distant galaxies are shifted to the rest frame, and the noise-weighted sum of the spectra is produced. This way, one can measure the average H I signal of the stacked galaxies. A great advantage of stacking is that by co-adding the spectra, one can boost the signal-to noise ratio, as the noise in the stacked spectra decreases with the square root of the number of stacked galaxies. Thus, this method is particularly useful to enhance the sensitivity of individually non-detected sources, not only in the nearby Universe, but also at large distances where the flux emitted by individual sources falls below the sensitivity limit of current radio telescopes.

The first H I stacking study was carried out by Lah et al. (2007) with the goal of measuring the average H I mass and cosmic density of neutral gas for galaxies at redshift $z = 0.24$. In a later study, Delhaize et al. (2013) carried out a similar stacking analysis up to $z = 0.1$. Besides cosmic density measurements of the neutral gas, stacking has been used for several other purposes in the last years. In two studies which were focusing on cluster galaxies at $z = 0.2$ and $z = 0.37$, Verheijen et al. (2007) and Lah et al. (2009) demonstrated that stacking techniques can be efficiently used to study the environmental dependence of the H I content. Stacking was used by Fabello et al. (2011a,b) to estimate the H I gas fractions in a volume limited sample of galaxies within the footprint of the ALFALFA survey in the redshift range $0.025 < z < 0.05$. They find that in massive galaxies (with stellar masses greater than 10^{10} $M_{\odot}$), the H I content most strongly correlates with the color and stellar mass surface density of the galaxies. These works ascertain that stacking is an efficient technique and it can be used in many ways to study, globally, the H I content of galaxies.

As the final noise depends on the number of stacked galaxies, one would need relatively large number of galaxies with available redshifts to achieve an adequate signal-to-noise ratio. Obtaining such a large number of spectroscopic redshifts requires a lot of observing time. To overcome these limitations, one possibility is stacking of wide-band interferometric data taken in sky areas covered by optical spectroscopic surveys, where many sources are available thanks to the large field-of-view of radio telescopes. In well-selected fields, optical surveys can provide the sufficient number of redshifts to reduce the noise significantly, i.e. the choice of radio data is set by the availability of the optical information.

In addition, confusion with nearby objects is less of a problem for interferometric observations. Spectroscopic surveys such as the Sloan Digital Sky Survey (SDSS, York et al. (2000)), not only provide the redshifts needed for stacking, but also plenty of information concerning the optical properties of galaxies, e.g., magnitude, color, emission line flux measurements. Consequently, an effective way to make full use of stacking is to combine the obtained H I and optical information with other multiwavelength data, e.g., infrared (IR), ultraviolet (UV). To get a more comprehensive view of the nature of the selected galaxies, the collected information can be used to define various properties of galaxy groups. One can measure the relative H I content of the sub-samples using H I stacking analysis, making it possible to study the role of H I in the evolution of different types of galaxies.

Why are multiwavelength observations useful?

One can collect multiwavelength information using the publicly available catalogs of sky surveys in the optical (SDSS), IR (Spitzer, WISE), UV (Galex), radio (NVSS, FIRST) wavelength regimes. Multiwavelength information allows us to study a number of physical processes for the following reasons. The radiation emitted by young stars falls in the optical and UV bands. Star-forming regions are often embedded in a dusty medium, where the emission coming from the young stars is re-emitted at IR wavelengths by the dust. Finally, supernova remnants can accelerate cosmic rays, producing synchrotron radio emission in the magnetic field of galaxies. Thus, flux measurements in the mentioned wavelength regimes can be used as an estimator for the star formation activity in galaxies (van der Kruit 1973; Condon 1992; Kennicutt 1998; Yun, Reddy, & Condon 2001). Furthermore, multiwavelength observations have been successfully used to study the active galactic nuclei of galaxies. For example, optical emission line diagnostics have been successfully used to separate star forming galaxies from Low Ionization Nuclear Emission Region galaxies (LINERs) and AGN (Kewley et al. 2001; Kauffmann et al. 2003). Mid-IR color-color diagrams can be used to identify AGN which are highly obscured by dust, and several studies have used this method when searching for AGN in the high redshift Universe (Lacy et al. 2004; Stern et al. 2005). These examples show that multiwavelength analysis is most useful to get a deeper understanding of the processes which dominate the electromagnetic radiation in galaxies.

1.4 Gas and the evolution of radio AGN

AGN activity is associated with accreting supermassive black holes (BH) in the central region of galaxies. Such BHs with masses in the range 10^6 - $10^{9.5}$ $M_\odot$ are thought to exist in every galaxy with a bulge component (Kormendy & Gebhardt 2001). The mass of the BHs was found to correlate well with the bulge velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000), suggesting that the formation of black holes and galaxies may be closely linked. Observational evidence suggests that black holes can grow through accretion of matter and by mergers with other black holes, and it is thought that gas plays an important role in these processes. It is believed that AGN are responsible for affecting the gas properties and evolution of galaxies by heating or driving the gas outside of the galaxy. AGN feedback was implemented in cosmological simulations, as an important element for making the predicted number counts of massive present-day galaxies match the observed values (Croton et al. 2006; Booth et al. 2009; Debuhr et al. 2012). Feedback can act through radiation, accretion-driven winds, radio jets, and these effects are thought to be responsible for suppressing star formation in massive galaxies and for regulating the growth of the BH. The estimated lifetime of radio AGN is relatively short. Although, the radio activity can be rejuvenated and galaxies can experience the feedback effects of their radio AGN recurrently (Saikia & Jamrozy 2009). Thus, one important questions regarding our understanding of active nuclei is whether AGN activity is usually episodic and if so, what is the cycle of the activity.

A commonly accepted model is that AGN activity is powered by material that is transported to the BH from the interstellar medium (Rees 1984). Due to conservation of angular momentum, the infalling material will form a flattened structure around the accreting BH. AGN can efficiently convert gravitational energy into radiant energy through an accretion disk, hence the classical AGN model (see Fig 1.2) has been built around this theory (Barthel 1989; Antonucci 1993; Urry & Padovani 1995). The main energy output of an accretion disks falls in the optical, UV, and X-ray part of the electromagnetic spectrum. Observational evidence supports that gaseous accretion disks are present in

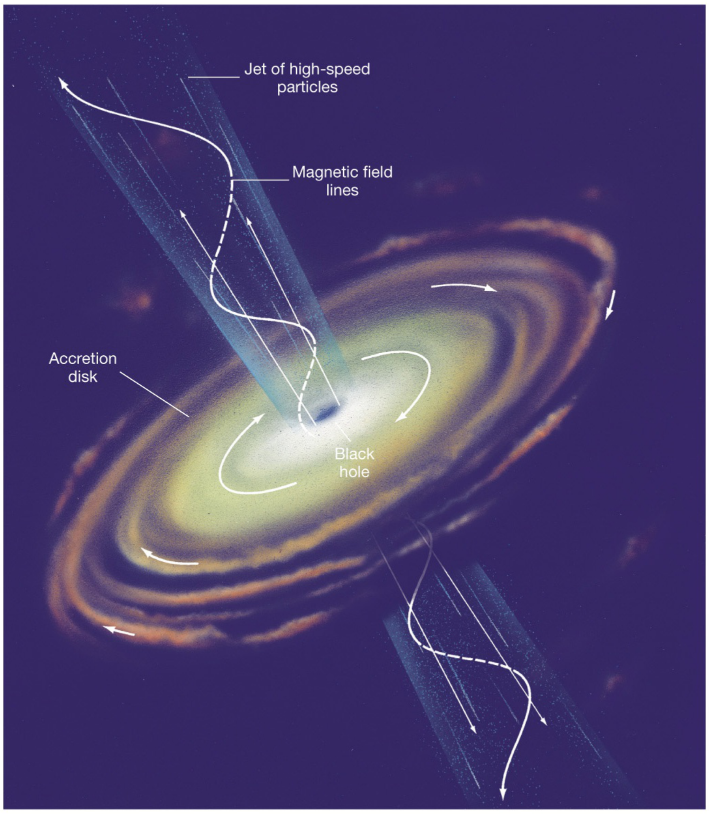

Figure 1.2: A model of AGN

many AGN (van Langevelde et al. 2000; Peck & Taylor 2001; Struve et al. 2010).

However, nuclear activity can reveal its presence in many ways. A particularly fascinating type of AGN are radio galaxies, which group are known for launching relativistic jets of radio plasma to large distances in the intergalactic medium (see Fig 1.3). Because accelerated particles in the magnetic fields of relativistic jets emit synchrotron emission at radio wavelengths, radio telescopes can be used to study the radio phase of AGN activity. In the classical scheme of unification theory it was suggested that orientation effects play a prime role in affecting our perception and observations of the AGN. If the accretion disk is oriented edge-on, we would detect the radio emission coming from the jets, while if the radio jets are pointed towards us, we can only detect the radiation of the accretion disk.

Even though orientation effects can play an important role, more recent studies argue that intrinsic differences could exist between different types of AGN (Hardcastle et al. 2007, 2009; Best & Heckman 2012). The main difference can be accounted trough the mode of accretion, as AGN activity occurs in at least two modes. The quasar-mode or cold-mode accretion happens through a radiatively efficient, optically thick and geometrically thin accretion disk, radiating across a broad range of the electromagnetic spectrum.

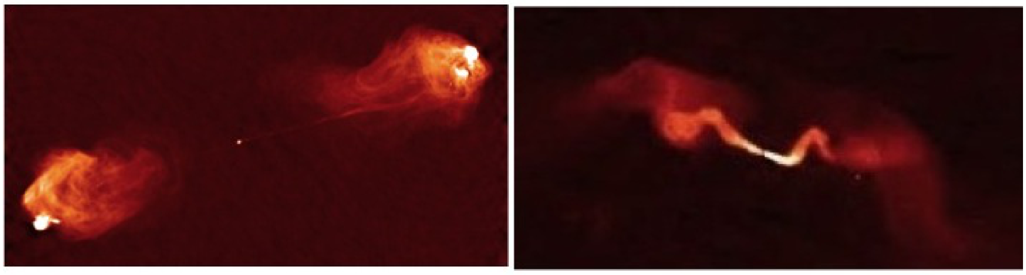

Figure 1.3: On the left: A classical case of FR II galaxies: Cygnus A (courtesy of C. Carilli, NRAO/AUI). On the right: FR I radio source in 3C 31 (credit: NRAO/AUI 1999)

However, it seems that not all AGN have an accretion disk in the classical sense of the word. It has been suggested that accretion can also happen through radiatively inefficient accretion. In this second AGN activity mode, the energy radiated through accretion is insignificant. However, the activity is revealed in form of highly energetic radio jets.

Based on the observed properties, radio galaxies can be separated into two main types according to the Fanaroff-Riley classification. These are the FR I and FR II sources shown in Fig. 1.3 (Fanaroff & Riley 1974). Although, the difference between the two types is far from being understood. FR II sources are powerful radio sources considered to be formed during gas-rich galaxy mergers. FR II-s have relativistic jets and edge-brightened lobes. FR I-s are less powerful sources, with edge-darkened lobes. A favored idea for the fuelling of FR I AGNs is quasi-spherical accretion of gas from the galactic halo or IGM (inter galactic matter) (Best et al. 2006; Hardcastle et al. 2007). However, the possibility of less violent 'dry mergers' – which occur amongst red, gas-poor early type galaxies – is also one possibility (Colina & de Juan 1995; Emonts et al. 2010).

Because nuclear activity and the mode of accretion in galaxies is regulated by the availability of the gas, it is crucial to get a better understanding of the physical and kinematical conditions of the gas in the circumnuclear region of AGN.

Probing the circumnuclear region of radio AGN via H I absorption

An important method of probing the circumnuclear region of galaxies is via H I absorption. If H I is located in front of a strong radio galaxy, it can be detected in absorption against the radio continuum of the AGN. Unlike H I emission, H I absorption strongly depends on the level of background continuum of the target source. Independently of the mass, H I absorption can be detected if the gas is optically thick. Thus, one can efficiently detect even small amounts of hydrogen in absorption at relatively high redshifts, while the sensitivity of present-day radio telescopes allows to observe H I emission only in the very local Universe.

The natural width of the hyperfine H I line is extremely small, about 1 km s^{-1} for gas of 100 K kinematic temperature. The line can appear broader due to non-zero temperature of the emitting regions or turbulence in the interstellar medium, however the most commonly observed broadening is due to Doppler shifts caused by bulk motions of the emitting gas relative to the observer, e.g. rotation, fast gas outflows. This means that H I can be used as a powerful tracer of the gas kinematics. Over the years, H I absorption observations contributed on a major scale for our understanding of the complex processes that occur in the nuclear region of galaxies. Absorption was found to trace a variety of structures in AGN: regularly rotating gas disks (Emonts et al. 2010; Gallimore et al. 1999), infalling H I clouds associated with the feeding mechanisms of the central black hole (van Gorkom et al. 1989; Morganti et al. 2009) and H I outflows tracing interactions between the jets and the surrounding medium (Morganti et al. 1998, 2003, 2005, 2013). Thus, the complexity of the H I kinematics in AGN suggests that gas can play many different roles in AGN.

A particular type of radio galaxies, compact steep spectrum (CSS) and gigahertz-peaked spectrum (GPS) sources are intrinsically small AGN (< 10 kpc), younger than $< 10^4$ yr (Owsianik & Conway 1998, Muria 1999). This type of radio source seems to be particularly rich in H I, while a large fraction of extended, FR I sources are undetected (Gupta et al. 2006; Emonts et al. 2010). According to the currently accepted paradigm, AGN activity is triggered in the compact phase by the infall of gas, thus CSS and GPS sources are the progenitors of extended FR I radio galaxies. van Gorkom et al. (1989) estimated that infalling clouds carry sufficient amounts of H I to trigger the nuclear activity in a sample of compact CSS and GPS sources. The estimated lifetime of radio AGN activity is $10^7 - 10^8$ years (Parma et al. 1999, 2007) and, according to van Gorkom et al. (1989), small amounts of H I with masses between 10^3 - 10^5 $M_\odot$ can fuel the AGN over this lifetime.

Other evolutionary theories suggest that not all compact sources evolve into extended sources (Emonts et al. 2010). This could happen for two reasons. Inefficient fuelling of the central black hole could prevent the source from becoming extended. The other possibility is that large amounts of dense interstellar gas could frustrate or even confine the growth of the central low-power AGN (van Breugel et al. 1984; Fanti et al. 1990; De Young 1993; Pihlström et al. 2003). However, it is not clear how severe the frustration of radio sources is, as hydrodynamical simulations (Wagner et al. 2012) and observational evidence (Morganti et al. 1998, 2005, 2013) show that interactions between the radio jets and the surrounding medium often result in fast outflows of cold gas. These results support that radio AGN feedback can have a major influence on the gas properties of galaxies.

One would expect that not just mechanical, but also radiative feedback has an effect, and gas outflows are quickly ionized by jet-cloud interactions. However, interestingly, previous studies have found that outflows in radio galaxies are predominantly cold. Both molecular and neutral gas outflows show relatively large mass outflow rates of a few $\times$ 10 $M_\odot$ yr^{-1}. It was estimated that the corresponding time depletion time scale is shorter than the typical lifetime of radio galaxies, suggesting that (cold) outflows are only present for a limited time in the life of a galaxy.

Broad absorption features associated to outflows are typically faint, showing, on average, low optical depth $\tau \sim 0.005$ (Morganti et al. 2005). Over the last years, the number of H I outflow detections has been increasing thanks to sensitive, broad-band observations, however the observed samples are still limited. It is clear that a full understanding of the properties of H I in radio AGN can only be achieved through the study of large statistical samples of galaxies. The observation of a large number of sources has the further advantage to allow stacking experiments.

Because both mechanical and radiative feedback processes can have important effects on the cold gas content of AGN, it is of interest to understand whether AGN activity is recurrent, and if so, how is this related to the H I properties. The structure and spectral index distribution of the lobes of radio galaxies provide important information on the history of the source (Saikia & Jamrozy 2009). Spectral and dynamical ages of these lobes could be used to constrain time scales of episodic activity. Over the years several features in radio sources have been suggested to be the signature of past activity. After the nucleus switches off, for lack of fuelling the lobe structure will fade away. However, for a limited time we can identify these structures through their fossil emission.

The main limitation of these studies is that at the moment only a handful of such radio relics are known. However rejuvenated sources represent a key element for our understanding of the AGN activity cycle, hence these objects are receiving more and more attention and the samples are increasing. It is particularly interesting to note that many of the restarted sources also show H I detection in their central regions (Saikia & Jamrozy 2009; Chandola et al. 2010; Shulevski et al. 2012). The frequent presence of H I in restarted AGN has been interpreted as a possible link between the presence of cold gas and AGN fuelling. In a way this is an intriguing discovery, as it is expected that AGN would get rid of the gas in the previous cycle of activity. The presence of H I suggests that cold accretion is not entirely suppressed by the AGN and, in fact, cold gas could be one of the key elements responsible for the reactivation of the radio source. A possibility other than continuous accretion from the environment is the hypothesis of positive feedback. In this scenario, if the velocity of the gas is too low to escape the gravitational potential of the galaxy, the gas will cool radiatively and resettle in a disk. However, at the moment this possibility is rather unexplored.

1.5 Questions addressed in this thesis

What is the global H I content of different types of galaxies? Does the H I content evolve as function of redshift?

One of our goals is to use stacking to measure the global H I content in galaxies up to redshift $z = 0.12$. We expand on previous studies mainly by using 'multicolor' information, and by separating different groups of galaxies based on optical emission lines, AGN diagnostics. Our analysis is also extended to higher redshift with respect to other stacking experiments, e.g. studies using Arecibo Legacy Fast ALFA Survey (ALFALFA) observations (Fabello et al. 2011a,b). It is interesting to investigate whether the higher star formation rate in the high redshift Universe is due to more efficient consumption of similar amounts of gas, or it is due to larger amounts of available cold gas at earlier epochs of galaxy evolution. By tracking the redshift evolution of the global H I content, we are interested in studying the efficiency of star formation in galaxies. This allows us to test the availability of gas and star-forming conditions at different epochs of the Universe.

What is the connection of H I with star formation and AGN activity?

An intriguing group of radio sources are the faint population of mJy and sub-mJy sources. At the sub-mJy level is difficult to disentangle whether star formation or radio AGN are the main contributors for producing the radio continuum emission. As both phenomena are extremely relevant in galaxy evolution, one would need to separate star-forming and nuclear processes in galaxies. In this thesis we discuss several diagnostics to identify

AGN, and we attempt to separate star-forming galaxies and AGN using multiwavelength information. In particular, we focus on the connection of the H I gas with star formation and BH feeding processes.

Do feedback processes deplete cold gas reservoirs in galaxies?
We investigate the effect of nuclear activity on the large scale gas content of galaxies. It is of our interest to study whether AGN can be responsible for depleting cold gas reservoirs in the not-so-distant Universe, or the gas is mainly consumed by star formation processes. To address this question, we target galaxies where feedback is more likely to be caught in action, namely AGN, and galaxies in the green valley (with older stellar populations compared to actively star-forming galaxies).

What are the gas conditions in the central region of AGN, and how is this related with the fuelling processes?
In this thesis, for the first time, we explore the possibility to detect central H I in AGN using H I absorption stacking. The detection rate and morphology of H I in early-type galaxies with/without AGN component can provide information on the conditions under which the nucleus is activated. To address the question whether radio activity is triggered by accretion of cold (H I) gas, we study the gas properties of young vs. evolved (i.e. compact, extended) radio sources. The kinematics of the gas can tell us about gas accretion history (inflows) and feedback processes by interactions between the radio source and the gas (outflows), thus we also study the gas kinematics in the two types of radio sources.

Are radio galaxies interacting with their ambient medium?
One of our goals for using absorption stacking experiments is to test the presence of H I outflows in AGN at low optical depth detection limit. We would also like to know how the gas depletion timescale compares to the life cycle of AGN. This can be important for constraining feedback models, and for our understanding of the interplay between AGN activity and H I gas throughout the lifetime of a radio AGN.

Restarted activity in AGN: does H I contribute to the fuelling processes?
At the moment it is still not clear whether radio AGN activity occurs in every galaxy, and what is the actual duty cycle of the radio phase. It is even more unclear whether the radio activity would be reactivated in all cases, and what is the cause of the rejuvenation. Because the available samples are limited, it is difficult to fully understand the role of H I in this process. We look for more cases of restarted radio sources and we study the H I properties of relic radio sources in this thesis.

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