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

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Summary

In this thesis we have used stacking techniques to study the H I gas properties of galaxies and AGN beyond the local Universe. We explore the possibilities and the science that can be addressed by applying stacking to archival datasets and to current/future wide-band observations, but also the technical limitations of such studies. An effective way to make full use of stacking is to select archival radio datasets in targeted fields with optical coverage, where one can combine the obtained H I information with optical data. Several datasets exist, e.g. in the WSRT (Westerbork Synthesis Radio Telescope) archive, that one could use to exploit the many opportunities given by stacking techniques. In this study we were able to understand important advantages of the technique, for example that even for datasets which are not entirely optimal for H I spectral line work (e.g. archival data with poor spectral resolution), stacking is giving promising results because the errors in the optical velocities are often of the order $50-75$ km s^{-1}. Less stringent calibration requirements make it easier to stack datasets originally calibrated for the continuum, and can also make it faster to fully calibrate and analyse data with automated pipelines. These aspects are also important for possible future stacking experiments.

Below we summarize the main conclusions from each chapter.

7.1 Chapter 2: The Lockman Hole project: gas and galaxy properties from a stacking experiment

- We detect H I in blue and red galaxies at $0.06 < z < 0.09$. As expected, blue galaxies are more H I rich, but also red galaxies which were selected based on $g - r$ optical colors do show relatively large amounts of H I in the stacked profile.
- In our galaxies a connection is found between the presence of neutral and ionized gas. All galaxies where H I is detected also contain ionized gas, whereas no H I is found around galaxies without ionized gas.
- Not just normal star forming galaxies, but also LINERs can have H I gas and on-going star formation
- LINERs can be separated into star-forming and non-star-forming groups based on IR colors. LINERs with ongoing star formation also show relatively large amounts

of H I and are often detected in the radio continuum. Non-star-forming LINERs resemble optically inactive galaxies, as this group is depleted of cold gas. Radio LINERs in the latter group are the best candidates for hosting low luminosity AGN.

7.2 Chapter 3: From star forming to inactive galaxies: the global cold gas content up to $z = 0.12$

- Galaxies in the green valley are detected with lower amounts of H I than blue galaxies, but unlike red galaxies (selected based on NUV - r colors), they are not completely depleted of cold (H I) gas. This result indicates that green valley objects are an intermediate population from H I point of view.

- We do not detect H I in red galaxies defined based on NUV - r colors. However, stacking is a promising technique to lower the detection limit and study the relatively unexplored $< 10^7$ $M_\odot$ H I mass regime of galaxies using large samples of galaxies.

- In agreement with previous studies, our results show that the presence of H I is better correlated with IR and NUV - r color rather than with ionization properties. We detect H I in AGN which were defined based on their optical emission lines. If they are classified as green/blue, even galaxies with higher ionization properties (LINERs and optical AGN) do contain cold gas. This suggests that optical AGN are not the (main) reason for depleting gas reservoirs, or that AGN-driven gas depletion is not an instantaneous effect in galaxies.

- In galaxies where cold gas (H I) is present, conditions are favourable for (residual) SF to be seen. Furthermore, in most of the sample, galaxies with more gas also have a higher SFR (blue cloud, SF galaxies).

- The H I mass-luminosity ratios do not change significantly as function of redshift, suggesting that the global H I content remains relatively constant up to $z = 0.12$. Furthermore, the global SFE displays a similar behaviour, remaining relatively constant in the covered redshift range. This can be interpreted as an indications that the H I content and SF are regulated by the same process, e.g. feedback effects, galaxy environment.

7.3 Chapter 4: Probing the gas content of radio galaxies through H I absorption stacking

- In a systematic study of the H I properties of radio AGN, we find that 30 percent is a representative H I detection rate for the general population of these objects.

- The detection rate does not depend on the apparent flux of a source, suggesting that H I absorption studies of even fainter radio sources will still bring a large number of detections. This result has positive implications for future surveys, which will observe AGN over a broad flux density range.

- We find a dichotomy in the presence of H I. Even when a large number of spectra are co-added, the stacking of undetected sources has resulted in a non-detection of H I. This suggests that there are objects genuinely depleted of H I or that orientation effects play a role. However, orientation effects alone cannot fully explain the dichotomy that we see in our sample, suggesting that some fraction of our galaxies must be depleted of cold gas.
- H I emission and absorption are tracing similar morphological structures. Compact, young AGN are richer in H I than the general population of early-type galaxies, supporting the hypothesis that nuclear activity in radio galaxies is triggered through feeding of cold gas.
- Compact sources show higher detection rates, optical depths and FWHM than extended sources, strongly suggesting that different gas conditions exist in these two types of radio sources; however, high resolution observations and a better measure of the covering factor are needed to confirm this result.

7.4 Chapter 5: The H I absorption 'Zoo'

- H I absorption displays a broad range of line shapes and kinematics. The busy function (Westmeier et al. 2014) provides a good tool for fitting and parametrizing the broad variety of absorption profiles.
- We find that the complexity of the lines is increasing with increasing profile width. Based on the line shapes and widths the lines can be separated into three groups belonging to different morphological structures. The narrowest lines with FWHM < 100 km s^{-1} in our sample are most likely produced by large scale disks or H I clouds. Relatively broad lines (100 km s^{-1} < FWHM < 200 km s^{-1}) may be produced by similar morphological structures with more complex kinematics. Broad lines with FWHM > 200 km s^{-1}, however, are tracing the most unsettled gas structures, e.g. gas-rich mergers and outflows.
- Broad lines show large asymmetries, and we note that symmetric broad lines are absent in our sample. The lack of symmetry could suggest that such broad profiles always arise due to unsettled gas.
- We detect three new cases of broad (FW20 > 500 km s^{-1}), blueshifted H I wings. Along with their radio source properties, i.e. powerful AGN with $\log(P_{1.4GHz})$ > 25 W Hz^{-1}, these sources are the best candidates for being jet-driven H I outflows. Considering certain and tentative cases, the detection rate of H I outflows is 5% in our total sample. The relatively low detection rate suggests that, if all radio AGN go through an outflow phase during their lifetime, then the gas depletion timescale of H I outflows is shorter than the typical lifetime of radio galaxies.
- H I in compact sources has a more unsettled distribution, e.g. blueshifted lines and broad/asymmetric profiles are frequent among compact AGN. Such H I line properties suggest that strong interactions between AGN and their rich circumnuclear medium are likely to occur as young radio jets are clearing their way through the ambient medium in the early phases of the nuclear activity.

7.5 Chapter 6: H I radio continuum, and optical properties of radio galaxies

- We have explored the presence of H I in a sample of SDSS/NVSS selected radio sources. We detect H I in the two brightest galaxies, however faint AGN cores, which are typical for extended sources, represent a bias against H I detection.
- H I in radio galaxies is connected with the radio source and star formation properties. We observe diffuse extended emission around both detected sources, likely due to the residual emission of a previous cycle of AGN activity.
- The detection of H I absorption in restarted sources suggests a link between neutral hydrogen gas and rejuvenation of nuclear activity, where possibly H I is the main fuel for feeding the central black hole. Signatures of restarted activity, e.g. relic radio structures seem to be a good indicator for the presence of H I absorption.
- Recent star formation events also show a close connection with the presence of H I. To make our conclusions more robust, based on a literature search we construct a larger dataset of radio sources with available H I observations. Galaxies with young stellar populations tend to show high H I detection rate, suggesting that star formation in radio galaxies is connected with the presence of an H I-rich medium.
- If gas accretion is a periodic event in radio galaxies, perhaps this effect will leave an imprint on the star formation history as well.

7.6 Future Prospects

This study has been limited by the number of objects due to the restricted availability of spectroscopic redshifts. The next step will be to increase the size and redshift range of the selected samples. Large H I surveys planned with new or upgraded radio telescopes will also improve the limitations of current H I observations due to their wide bandwidth, high spectral resolution and increased field of view. In particular, the combination of large surveys and wide bandwidth promised by the future focal-plane array receivers to be installed for Apertif (Oosterloo et al. 2010b), the Australian Square Kilometre Array Pathfinder (ASKAP, Johnston et al. 2008; DeBoer et al. 2009), will provide favourable observational settings to combine the radio continuum and H I spectral line data with optical information, and thus to trace, for the first time, the cosmological evolution of neutral hydrogen.

Using stacking techniques, we have reached the M_{HI} detection limit of a few $\times\ 10^8$ $M_\odot$ for galaxies which have been observed for 12 hours with the WSRT, in the redshift range $z < 0.1$. Even though this is a relatively low limit, lower H I masses have been detected before in `SAURON` and ATLAS^{3D}. Future, large surveys will provide enough data to test the global H I content at earlier epochs of the Universe at lower, currently rather unexplored H I detection limit of $M_{HI} < 10^7$ $M_\odot$. Stacking is a promising technique to reach this limit, given that large samples of galaxies are available with spectroscopic redshift measurements. This will be made possible by future H I surveys with the next generation of radio telescopes, e.g. Apertif, ASKAP, and MeerKat (Booth et al. 2009). Currently the studied samples are biased by the optical selection of the SDSS. Future surveys will expand on the work presented here by searching for H I in a 'blind' mode, allowing for the detection of the H I population without any optical pre-selection.

Large samples with available multiwavelength data also make it possible to study and compare the H I properties of subsamples with different color, ionization properties, stellar populations, etc. The success of these studies highly depends on the availability of ancillary data. Thus, the most effective way of carrying out such an analysis is to observe H I in the area of well studied fields, for example the Lockman Hole (Fotopoulou et al. 2012), the COSMOS field (Fernández et al. 2013). Furthermore, we expect that in a larger sample the number of potential AGN (optical and/or radio) will increase, making it possible to further investigate the connection between gas and the black hole activity.

Unlike H I emission, H I absorption studies are less limited by sensitivity in the higher redshift Universe. Our results suggest that the detection rate of H I absorption does not depend on the apparent flux of a source and this has positive implications for future, deeper surveys. These large-area surveys will uncover a very large number of H I absorptions systems. At radio power lower than $< 10^{23}$ W Hz^{-1} we expect a mix of star-forming/AGN populations (Mauch & Sadler 2007). If emission and absorption are tracing similar morphological structures, H I absorption studies can be used just as efficiently to find cold gas not just in AGN, but also in star-forming galaxies at higher redshift. The increased number of sources will provide enough data to perform H I stacking experiments and, hence, to probe the highest redshift regime of the observed radio sky at low optical depth.

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