# HI gas in galaxies from z = 0 to z = 0.2

Jacqueline van Gorkom

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# HI gas in galaxies from $z = 0$ to $z = 0.2$

Jacqueline van Gorkom

*Columbia University*

**Abstract.** Probing the evolution of galaxies through the neutral hydrogen window has until recently been limited to studies of environmentally driven evolution in the local universe. Detailed imaging studies of galaxies in Virgo and volume limited surveys of clusters out to $z = 0.08$ show that ram pressure stripping is one of the mechanisms that drives galaxy evolution even at considerable distances from the dense cluster cores. Hydrodynamical simulations show that indeed the effects of the ICM are felt out to the virial radius due to the complex structure of the ICM. Westerbork and Arecibo have begun to observe galaxies at cosmologically interesting distances ($z = 0.2$). Soon the EVLA will be able to make a complete census of all H I emission in cones of $40' \times 40'$ probing an instantaneous velocity range from $z = 0$ to 0.53, with a resolution of a few arcsec. If prime focus feeds were to be installed at the EVLA those studies could easily be extended out to $z = 1$ in the coming decade, making the EVLA a prime pathfinder for H I studies with the SKA.

**Keywords:** galaxy evolution; H I line emission
**PACS:** 98.62.Ai

## INTRODUCTION

In current scenarios of the formation and evolution of galaxies dark matter halos grow by merging, gas falls into these halos, cools and forms stars. Currently there is much debate about the physics of the gas accretion, does gas first get shock heated to the virial temperature of the halo and then cool and accrete, or does it never get shock heated and does it flow in directly [1].

Some of the main questions that we want to address in studies of the role of gas in galaxy evolution is:

- How and when did galaxies accrete their gas?
- Where and when do galaxies stop accreting cool gas?
- How do galaxies loose their cool gas?
- How do galaxies stop forming stars?

Although the theme of this conference is galaxy evolution as probed through the neutral hydrogen window, so far we have no direct measures of these evolutionary effects based on emission studies. The most distant H I emission that has been detected is at a redshift of $z \approx 0.2$. Yet we have learned a lot about more distant H I from absorption line studies, most notably the Ly$\alpha$ line. Although these studies are tremendously valuable, they do not give us direct answers to any of the questions posed above. We need emission line studies to answer these in detail. In this talk I will describe a few things that we have learned about galaxy evolution through the neutral hydrogen window, specifically about environmentally driven evolution in the local universe, I will also present some the

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results obtained at $z = 0.2$ with an emphasis on what will be possible in the near future and what could possibly be done in the more distant future at the VLA.

## GALAXY GROWTH

Galaxies can grow by accretion of gas, by merging with gas rich galaxies and lastly by merging with gas poor galaxies. Mergers between gas rich galaxies have been observationally studied in great detail [see e.g. 2] and H I observations have been very useful to study the fate of gas in mergers and merger remnants [3].

Although it is generally assumed that continued infall of gas from the intergalactic medium does happen, direct observational evidence for this has only been acquired recently. Deep observations and careful modelling of NGC 2403 and NGC 891 by Fraternali and collaborators provide the first evidence that HI is really falling in [4] and almost certainly originates at least partly in the intergalactic medium. We have no idea yet whether this is a general phenomenon in nearby galaxies and whether it depends on galaxy mass or environment. At the high mass end we have the so called red and dead galaxies. There is a general consensus that most stars in these galaxies formed at redshifts beyond 2, but observations seem to indicate that the mass in the red galaxies has increased by a factor 2 between $z = 1$ and 0. To resolve this dilemma people have postulated that these galaxies grow by dry (dissipationless) merging between gas poor galaxies. The challenge is now to find the remnants of the dry mergers. Van Dokkum [5] has identified dry merger remnant candidates from an analysis of the NOAO Deep Wide Field Survey. Although the mean redshift of those systems is 0.1, it is even for those systems a challenge to get the neutral hydrogen content. Donovan et al. [6] have taken the opposite approach and have looked whether nearby known gas rich merger remnants would have been selected by van Dokkum as dry mergers. Fifteen out of twenty gas rich remnants satisfy the color cut imposed by van Dokkum. Colors alone are not enough to establish whether a merger is dry, we need to observe the gas.

## ENVIRONMENTALLY DRIVEN GALAXY EVOLUTION

While we saw in the previous section that H I observations are only now beginning to contribute to our understanding of the growth of galaxies, studies of the gas content and morphology of galaxies in the local universe have become very useful to study environmentally driven galaxy evolution. The density morphology relation has been known for almost half a century, showing that the morphological mix, star formation properties and luminosities of galaxies all differ significantly in dense cluster cores from the field. In recent years observational evidence has accumulated that many of these properties change very smoothly as function of projected distance from the cluster centers to surprisingly large distances. In a sample of 18 nearby clusters the H I deficiency shows a very gradual decline out to two Abell radii [7]. The star formation rate declines in a similar fashion in clusters at intermediate $z$ [8], while a gradual change in morphological mix out to 5 Mpc is seen for a cluster at $z = 0.4$ [9]. This is surprising because the impact of the intracluster medium (ICM) and that of the cluster potential on individual galaxies is generally not expected to extend much beyond about 1 Mpc from the cluster center.

While the SDSS and 2dF surveys have been used to study environmental effects, those studies are not easily comparable to the studies centered on clusters and their environments because they combine galaxies at the same local galaxy density in a wide range of global environments. Here I want to focus on a narrow, but well defined, environmental range, from the cluster core to the low density outskirts.

Neutral hydrogen as a galaxy's cool gas reservoir is an excellent probe of the impact of environmentally driven evolution. In regions of high galaxy density environmental effects can roughly be divided in gravitational and gas-gas interactions. Gravity will affect both gas and stars, while gas-gas interactions wil only affect the gas. Several H I imaging surveys have been performed or are being carried out aimed at exploring what is happening in the very outer parts of clusters.

## The Virgo Cluster

A new VLA imaging survey has been performed of selected galaxies in the Virgo cluster that probes a much wider range of galaxy density environments and goes down to fainter magnitudes than previous survey. A summary of the main highlights is given in [10]. One of the more striking findings shown in Figure 1 is that seven galaxies at intermediate distances from M87 have long one sided H I tails pointing away from the cluster center [11]. For several of these galaxies the H I is stripped to within the optical disk on the side pointing toward M87, which strongly suggests that ram pressure stripping takes place. Although it is somewhat surprising that ram pressure stripping takes place that far from the center, for most of the seven galaxies it is a plausible explanation since it is the low density gas in the very outer parts of the disks that is being removed. We are watching the onset of the environmental impact on galaxies that are falling in for the first time [11].

NGC 4522, a galaxy even further out in Virgo, represents an entirely different case. It has an optically undisturbed disk, while the H I is spatially truncated to well within the disk at 3 kpc (0.4 $R_{25}$) and significant amounts of extraplanar H I exists on one side of the disk close to the truncation radius [12]. This implies that contrary to the tail galaxies mentioned above it must be experiencing or have experienced strong ram pressure. The apparent contradiction is that at the current location of NGC 4522 the estimated ram pressure is an order of magnitude too small. Other data confirm the picture that the stripping is a recent or ongoing phenomena. [13] find a ridge of highly polarized radio continuum in the disk, a flat spectral index and peak polarization at the location where ram pressure appears to be highest, suggesting compression of the magnetic field lines at the leading edge of the ICM-ISM interaction. Crowl and Kenney [14] using integral field spectroscopy find that the star formation in the stripped outer disk ceased very recently, about 100 Myr ago. A dynamical model using both the H I and polarization data [15] finds that peak pressure must have occurred 50 Myr ago. Yet at its current location the ICM density near NGC 4522 it too low by an order of magnitude to provide the needed ram pressure, while the galaxy is so far from the center that it would have taken the galaxy at least 500 Myr to travel from a location where the ICM density is high enough

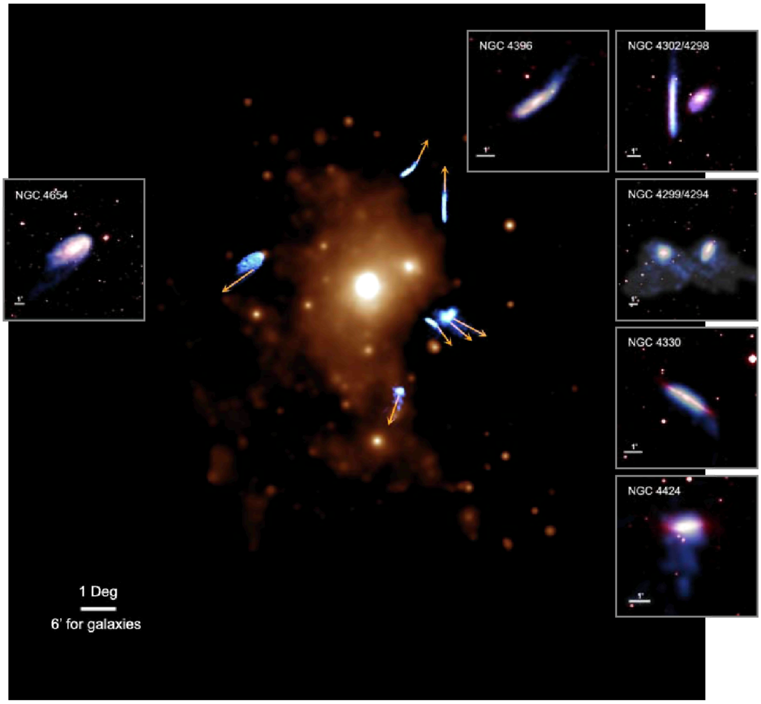


**FIGURE 1.** One sided H I gas tails pointing away from M87 [11]

to its current location. A suggested solution to this apparent contradiction is that the ICM near NGC 4522 has been stirred up due to the ongoing cluster-sub cluster merging with the M49 group [12]. Below I will show more results that suggest that it is at the interface of cluster-subcluster merging where galaxies get strongly affected by the ICM. The Virgo survey shows that galaxies will get stripped of their gas in the center of the cluster and that some might already get stripped in the outskirts due to a dynamical and clumpy ICM. Chung et al. [16] show that stripping has a significant effect on the color evolution of the galaxies.

## Clusters between $z = 0$ and $z = 0.08$

Another large program at the VLA [17] is aimed at imaging in H I the total volume of a sample of clusters between $z = 0$ and $z = 0.08$. Contrary to the Virgo study of pointed observations at individual galaxies, here each cluster is covered in a mosaic of 3 to 16 pointings and covering a velocity range of 5000 km s$^{-1}$. The mosaics go out to two Abell radii in order to probe both the cores and low density outskirts. A summary of the results is shown in Figure 2. Although we cover each cluster to the same H I mass limit, the difference in detection rate is striking. The detection rate appears to

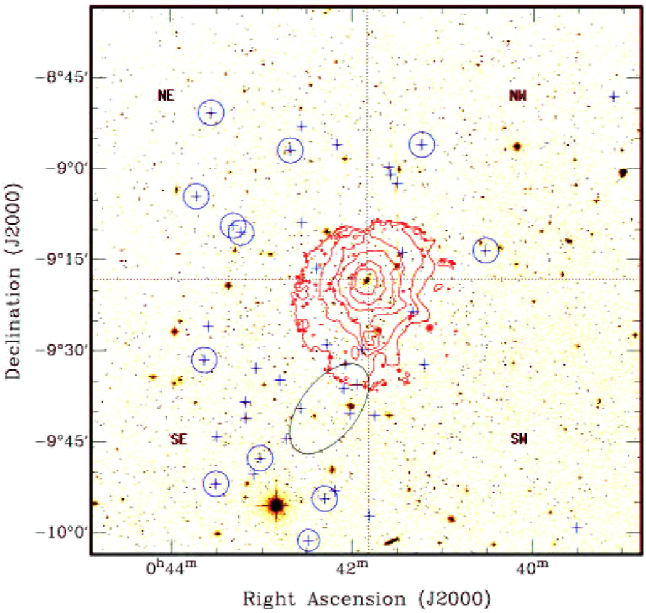


**FIGURE 2.** Total H I image of Abell 85, which is currently merging with subcluster falling in from the south east. Red contours X-ray emission. The H I detections (blue circles) are all east of the cluster. Note the blue undetected galaxies (blue crosses) at interface between subcluster cluster merger [18]

be related to the dynamical state of the clusters. We detect of order 50 galaxies in the premerger clusters Hydra and Abell 2670, in Abell 496 and Abell 85 a cluster subcluster merger is currently in progress and we detect 25 and 10 galaxies respectively. Abell 85 is especially interesting since all the detections are to the east of the cluster, while at the interface between the cluster and subcluster a number of blue, non H I detected galaxies are found [18]. This seems similar to the M87 and M49 interface where in addition to NGC 4522 several very gas poor galaxies are found. In Abell 754 a merger has recently happened [19] and we only detect one galaxy in H I. The merger apparently stripped all galaxies in the environment of their H I. So in conclusion it seems that the H I detection rate depends on the dynamical state of the cluster.

## Galaxy Evolution in Cosmological Simulations of Cluster Assembly

The data of the Virgo survey are being used to constrain simulations of individual galaxies in the cluster [15]. Simulations can also be used to explore how important different environmental effects may be for the evolution of galaxies. Tonnesen et al.

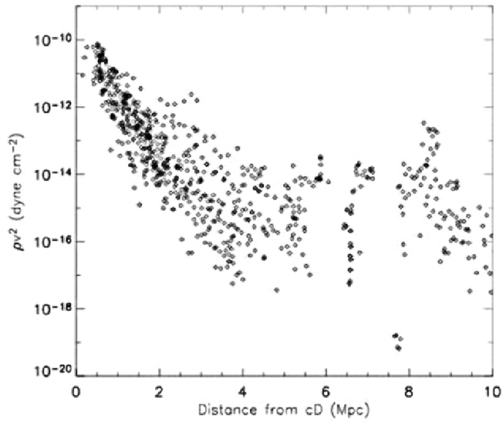


**FIGURE 3.** Ram pressure as function of distance from the cD in a simulated cluster[20]

[20] use a hydrodynamical cosmological simulation of cluster formation and evolution to examine the evolution of galaxies therein. They follow a large number of galaxies over time and track each galaxy's gas and stellar mass changes to explore what mechanisms dominate the evolution of the galaxies. Although gas is lost due to a wide variety of mechanisms, the dominant event is a gas-stripping only event and the amount of gas lost correlates with the ram pressure the galaxy is experiencing. Interestingly although most of the gas loss occurs in the central Mpc of the cluster, some galaxies get stripped without ever coming that close to the center. This is due to the wide scatter of ram pressure strength is found at fixed distance from the cluster (Figure 3). These results appear to be consistent with the observational results. The complex and constantly changing structure of the ICM, as subclumps continue to merge with the clusters, can affect galaxies at large distances from the cluster center.

## H I AT COSMOLOGICAL DISTANCES

Obviously we would love to know how the H I content of galaxies evolves with redshift. It has been known since the early eighties that already at redshifts of $z = 0.2$ clusters of galaxies begin to differ from clusters in the local universe [21] with a larger fraction of star forming galaxies at higher redshifts. It has now become possible to observe galaxies in H I emission out to at least $z = 0.2$. At this conference we heard that Arecibo has detected isolated gas rich galaxies at those redshifts in just a few hours of observing time [22]. The Westerbork Synthesis Radio telescope has recently been upgraded, making it possible to instantaneously observe a velocity range of 18 000 km s$^{-1}$ with a velocity resolution of 10 km s$^{-1}$ or so. Its high angular resolution ($\approx 20''$) and wide field of view (8 Mpc $\times$ 8 Mpc) make it eminently suitable to do a survey of a large volume at higher redshifts.

Verheijen et al. [23] recently published the results of a pilot for such a survey of two clusters at $z = 0.2$ and the large scale structure in which they are embedded. Figure

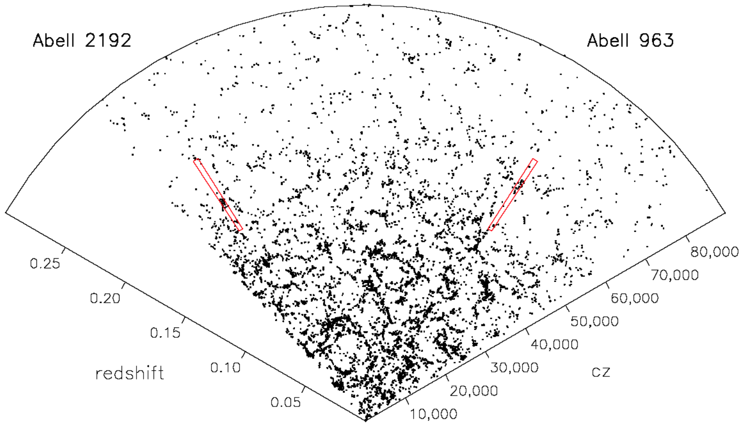


**FIGURE 4.** The volumes surveyed by the WSRT ($8.2 \times 8.2 \times 326$ Mpc$^3$) are indicated by the red boxes [23]. The EVLA will be able to probe in one pointing an even larger volume, a similar sized cone but in velocity covering from $z = 0$ to $z = 0.53$

4 shows a slice from the SDSS and superimposed the area around the clusters probed by the WSRT. Although this was only a pilot of 200 hours per cluster, 42 galaxies are detected in H I. The data quality is high enough to derive rotation curves for individual galaxies (Figure 5). Most importantly already interesting science is coming from the pilot. One of the clusters, Abell 963, was one of the first Butcher Oemler clusters detected, it has a blue fraction of 20%. Interestingly while the WSRT detects the blue galaxies outside the cluster, none of the blue galaxies found by Butcher and Oemler in the central Mpc are detected. Hence it must be the location of these galaxies that makes them special. They are probably in their last phase of star formation. Verheijen et al are now carrying out a survey to greater depth (1000 hours per cluster) and soon the H I properties of hundreds of galaxies in the clusters, filaments and voids will be known at $z = 0.2$.

## THE FUTURE

To get anything close to an understanding of how galaxies form and evolve we will need as a first step to image the gas content of individual galaxies as function of redshift and environment. What are our prospects for that work in the pre SKA age? At this conference we have seen that both Arecibo and the WSRT have begun to observe galaxies at cosmologically interesting distances. There is no reason why Arecibo couldnot go to even higher redshifts to get the H I content of isolated systems. The WSRT is giving us a taste of what the EVLA will be able to do even better. Not only does it have twice the collecting area of the WSRT and 10 times better resolution, its new backend will allow for an instantaneous velocity coverage of $z = 0$ to $z = 0.53$ with 10 km s$^{-1}$ velocity resolution. In a few hundred hours it will be possible to get the entire H I content of galaxies in a cone of $40'$ by $40'$ from $z = 0$ to 0.53, with exquisite

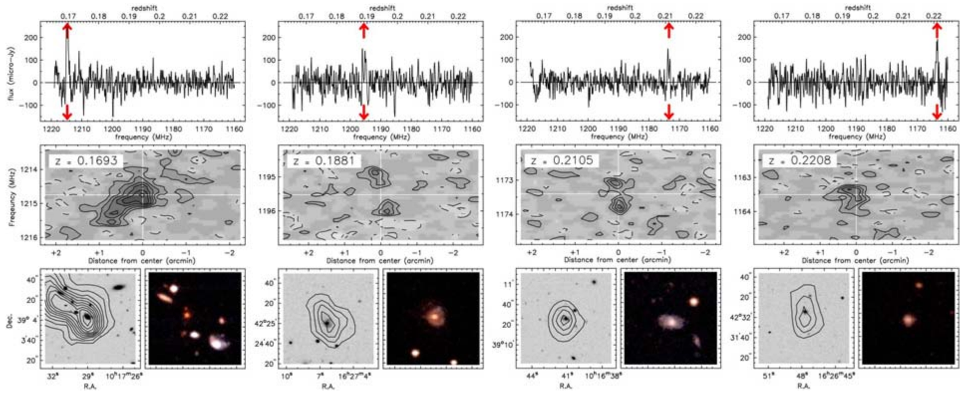


**FIGURE 5.** H I profiles, position velocity diagram and overlays on optical images of some of the H I detections at $z = 0.2$ [23]. Note that data quality is high enough to derive rotation curves for some.

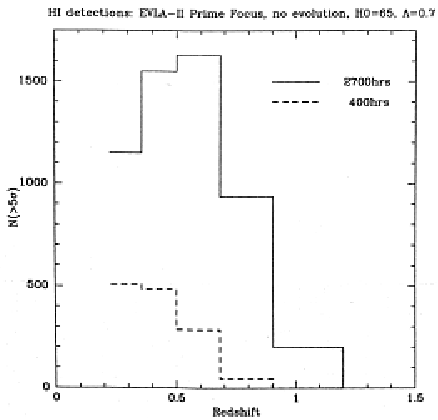


**FIGURE 6.** The H I Universe as seen in a single EVLA pointing, if the prime focus feeds were to be installed. The histograms show the galaxies detected ($5\sigma$) in 400 (dashed) and 2700 (solid) hours integration, assuming no evolution. The lack of galaxies at $z \leq 0.2$ is due to the fall-off in sensitivity of the proposed prime focus system above 1.2 GHz. Histogram taken from EVLA science case

detail for individual nearby galaxies and solid measures of content and rotation curve for galaxies even at $z = 0.53$, probing clusters,voids and filaments. The EVLA will be fully operational in 2012. An even more interesting prospect is that NRAO is considering the installation of prime focus feeds that would cover the frequency range from 1200 to 500 MHz. Then it would be possible to observe in one observation a slice from $z = 0.2$ to 0.8. The expected detection rates for different integration times assuming no evolution of HI content are given in Figure 6. It seems that the future looks very bright indeed. The EVLA will be a prime SKA pathfinder for H I studies in the decade to come.

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