Outskirts of Galaxy Clusters: intense life in the suburbs
Proceedings IAU Colloquium No. 195, 2004
A. Diaferio, ed.

DOI: 00.0000/X000000000000000X

Galaxy evolution in dense environments; a concise HI perspective.

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Abstract. Observing the neutral Hydrogen in galaxy clusters provides crucial insights in the physical processes that influence the evolution of gas-rich galaxies as they migrate from the lower-density filaments through the cluster outskirts into to the higher-density central regions. The morphology-density relation, the Buther-Oemler effect, and the observed HI deficiencies in the central regions of galaxy clusters suggest that infalling galaxies experience a strong transformation of their morphologies, star formation rates, and gas content. The physical mechanisms that trigger and govern these transformations may depend strongly on environment. This contribution aims to illustrate that the morphological and kinematic characteristics of the cold gas provide a sensitive tool to determine which mechanisms dominate in which environments.

1. Motivation for observing the cold gas.

Hydrogen is the most abundant primordial baryonic matter in the Universe out of which the visible galaxies and galaxy clusters have formed. Observations of the distribution and kinematics of cold neutral Hydrogen at the epoch of galaxy formation, and during their subsequent evolution, provide one of the most direct windows on the physical processes involved. Numerous studies indicate that the pace of a galaxy's evolution, like its growth by mass accretion, the rate at which it forms stars, the frequency of tidal interactions and the occurrence of minor or major mergers, depends significantly on its local and global environment. In particular the environment encountered in the outskirts of galaxy clusters is very favorable to rapid evolution and transformation of galaxies as they fall in along the lower-density filaments into the higher-density cluster cores. Such infalling galaxies encounter an increased local galaxy density, which results in more frequent tidal interactions, and they may be confronted with a hot Intra-Cluster Medium (ICM) as they approach the cluster core. This change of environment can have a dramatic impact on a galaxy's morphology, its gas content and its star formation rate. This is also implied by the well-known morphology-density relation combined with the notion that clusters continue to accrete galaxies from the surrounding large scale structure in which they are embedded. Consequently, infalling galaxies must experience a signifiant transformation on a relatively short time scale, which is also suggested by the Butcher-Oemler effect and the interpretation that the blue galaxies in the outskirts of galaxy clusters experience a period of vigorous star formation which can end abruptly once all the cold gas is consumed or removed. These galaxies eventually find themselves in the cluster core as gas-poor systems with a passively evolving stellar population.

The presence of cold gas in galaxies is a prerequisite for star formation, and the amount and distribution of cold gas regulates the duration and intensity of star formation periods. The removal of this cold gas reservoir from infalling galaxies is a crucial element in the process that transforms these systems. The key question is which physical processes trigger and govern the enhanced star formation, and the removal of the cold gas. What is the role and ultimate fate of the cold neutral Hydrogen in infalling galaxies?

Table 1. Galaxy clusters imaged in neutral Hydrogen, compiled from the literature and from work by the author and his collaborators.

Cluster	z	σ km/s	N_z	T_{B-M}	C	R	L_X 10^{44}erg/s	f_b	Array	Mode	# Flds	N_{det}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Ursa Major	0.003	149	96		26				WSRT	pointed	65	70
									VLA	blind	56	
Virgo	0.004						1.00	0.04	VLA	pointed	23	23
Hydra	0.013	676	256	III	50	1	0.47		VLA	vol. lim.	13	49
Abell 3627	0.014	897	112	I	59	1	2.2		ATCA	pointed	3	2
Abell 262	0.016	415	>38	III	40	0	0.55	0.02	WSRT	pointed	5	11
Coma	0.023	880	$\sim10^3$	II	106	2	7.21	0.03	VLA	pointed	12	39
									WSRT	blind	mosaic	
Abell 496	0.033	657	238	I:	50	1	3.54		VLA	vol. lim.	10	46
Hercules	0.037	887	>42	III	87	2	0.88	0.14	VLA	blind	4	61
Abell 754	0.054	1048	408	I-II:	92	2	8.01		VLA	vol. lim.	2	4
Abell 85	0.055	1443	275	I	59	1	8.38		VLA	vol. lim.	8	23
Abell 2670	0.076	908	219	I-II	142	3	2.55	0.04	VLA	vol. lim.	3	49
Abell 2218	0.176			II:	214	4	8.99	0.11	WSRT	vol. lim.	1	1
Abell 2192	0.188	706	36	II-III:	62	1			VLA	vol. lim.	1	1
									GMRT	vol. lim.	1	0
Abell 1689	0.183	1253	525	II-III:	228	4	20.74	0.09	VLA	vol. lim.	1	0
Abell 963	0.206		~200	I-II	134	3	10.23	0.19	WSRT	vol. lim.	1	0

Ursa Major: Verheijen & Sancisi (2001), Verheijen *et al.* (2001). Virgo: Cayatte *et al.* (1990).
Hydra: McMahon (1993). A3627: Vollmer *et al.* (2001). A262: Bravo-Alfaro *et al.* (1997).
Coma: Bravo-Alfaro *et al.* (2000), Beijersbergen (2003). A496: van Gorkom *et al.* (in progress).
Hercules: Dickey (1997). A754: van Gorkom *et al.* (in progress). A85: van Gorkom *et al.* (in progress).
A2670: Poggianti & van Gorkom (2001). A2218: Zwaan *et al.* (2001). A2192: Verheijen *et al.* (in progress).
A1689: Verheijen *et al.* (in progress). A963: van Gorkom *et al.* (in progress).

2. Physical processes.

Observing the cold gas in transforming galaxies inherently provides important clues about the physical processes that lead to its removal. Many mechanisms have been proposed that could result in the depletion of the cold gas. Only some are mentioned here.

The fragile extended gas disks of spiral galaxies are effective tracers of tidal interactions. Tidal interactions between galaxies, either by a few slow but effective encounters or by many 'harassing' fast encounters (e.g Moore *et al.* 1996), may result in the removal of cold gas from the tenuous outer regions, leading to truncated HI disks. Once an infalling galaxy encounters the hot ICM, the cold gas may be removed by ram-pressure, and turbulent and viscous stripping (e.g. Schulz & Struck 2001; Abadi *et al.* 1999), provided the ICM is sufficiently dense and the galaxy moves fast enough. Ram-pressure may also compress the cold gas clouds, triggering enhanced star formation. The cold gas could also be removed by more gentle and slower processes like thermal evaporation of the ISM by the hot ICM, provided there is sufficient thermal conduction (e.g Cowie & Songaila 1977). The slow removal of the cold gas, regardless of the physical process, was labeled 'starvation' by Treu *et al.* (2003). Besides the physical removal of the cold gas from the gravitational potential, a triggered burst of star formation may quickly consume all the cold gas and lock it up in a new generation of stars. This exhaustion of the cold gas

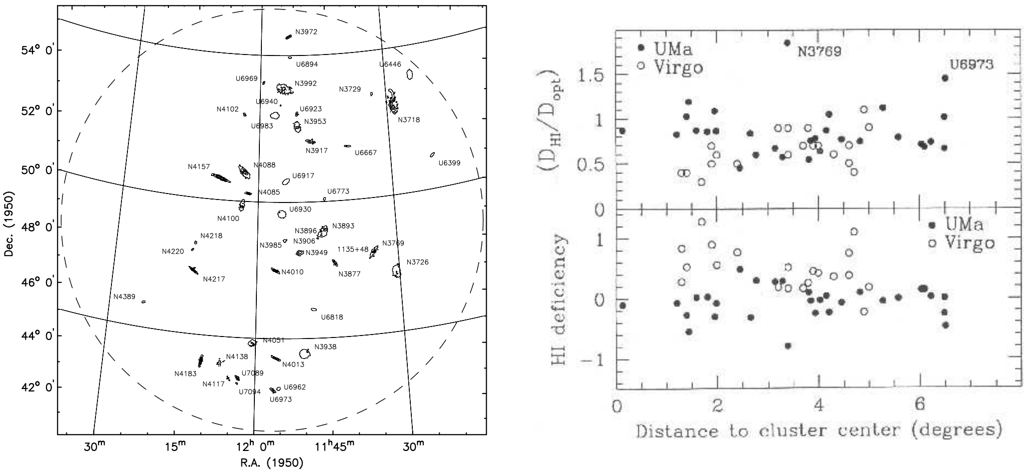

Figure 1. Left: Composition of integrated maps of atomic hydrogen in the Ursa Major cluster. Individual galaxies are 4× enlarged. **Right:** A comparison of HI properties of galaxies in the Ursa Major and Virgo clusters as a function of projected distance to the cluster center. Above: ratio of HI to optical diameters. Below: overall HI deficiency as a function projected distance.

reservoir can be achieved within a few$\times 10^7$ years during a dusty and possibly obscured star burst. Luckily, the radio continuum emission, a by-product of HI synthesis imaging, can be used to derive star formation rates which are unaffected by dust extinction, although contamination by AGN activity may be significant.

Apart from providing insights in the physical processes mentioned above, neutral Hydrogen observations may also help to determine the amount of substructure, the mass accretion rate, and the dynamical state of galaxy clusters. A volume limited survey reveals the location of all the gas-rich galaxies, and helps to map the large scale structure in which these galaxy clusters are embedded. For instance, if a subclump of galaxies is observed to be gas-rich, it is quite unlikely it has crossed the high density cluster core on its infall trajectory. Furthermore, in case the cold gas is in the process of being removed from the plane of an infalling galaxy, its offset may indicate the direction in which a galaxy is moving and thus help to constrain its orbit.

Finally, observed metal abundances of the ICM suggest that at least some of it finds its origin in the Inter-Stellar Medium (ISM) and it would be interesting to know how much the effect of ram-pressure stripping contributes to this.

3. Galaxy clusters imaged in HI.

In order to investigate the role that the cold gas plays in the transformation of infalling galaxies, and the influence of the environment on the various physical processes, a significant sample of galaxy clusters has been and is being imaged in the 21cm line of neutral Hydrogen. Table 1 provides an overview of these clusters, complemented by existing studies from the literature. The clusters span the full range of redshifts practically accessible by present day telescopes, up to a redshift of 0.2 where the nearest Butcher-Oemler clusters are found. The clusters also span a range in richness, X-ray luminosity and dynamical state. Some clusters display significant substructure while others, like Abell 963, seem to be fully relaxed. These clusters and their surroundings encompass a large variety of environments, ranging from the most dense cluster cores to areas of

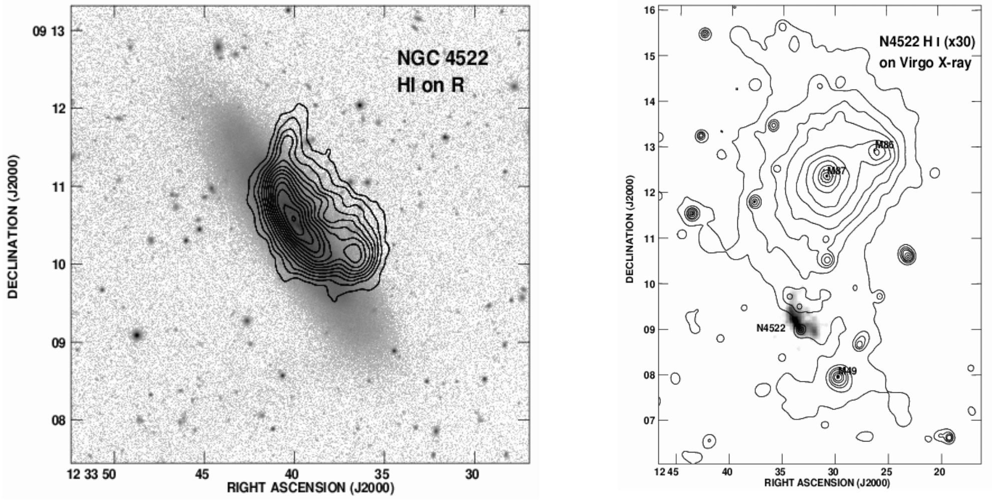

Figure 2. Left: NGC 4522 in the Virgo cluster. The HI contours are displaced from the optical disk and clearly show the sweeping effect of ram-pressure stripping. **Right:** The location of NGC 4522 with respect to the distribution of X-ray emitting gas in the Virgo cluster. Figures taken from Kenney, van Gorkom & Vollmer (2004).

significant underdensity. One example of a low density diffuse cluster is presented in the left panel of Figure 1; Ursa Major.

4. Some phenomena observed in HI.

Several intriguing and revealing phenomena have been observed in neutral Hydrogen, and some of these will be illustrated here. First of all, from spatially unresolved single dish studies, there were strong hints already in the seventies, that galaxies in cluster cores are relatively poor in HI compared to their counterparts in the lower density field. The meaning of this HI deficiency became more clear with the advent of HI imaging data from the Very Large Array of galaxies in the Virgo cluster, as illustrated in the right panel of Figure 1. The gas disks of galaxies within 2 degrees from M87 are smaller than those of galaxies further away from the cluster center. At 4 degrees from the cluster center, the gas disks in Virgo seem to be of comparable size to those in the lower density Ursa Major environment (upper panel), but the Virgo galaxies are still more deficient in HI (lower panel); it suggests that the overall column densities of the gas disks in Virgo are lower compared to the Ursa Major galaxies. This illustrates that HI imaging gives crucial physical meaning to the notion of HI deficiency.

Early HI imaging data of the Coma and Virgo clusters showed that the gas disks of galaxies in the outskirts of galaxy clusters can be asymmetric, both morphologically and kinematically, and significantly offset from the stellar disk of a galaxy. The spectacular example of N4522 in the Virgo cluster has been recently published by Kenney, van Gorkom & Vollmer (2004) and is reproduced in Figure 2. The small gas disk is clearly offset from the stellar disk and seems to be bend and swept away from the plane, interpreted to be the result of ram-pressure stripping. The right panel of Figure 2 indicates the position of this galaxy with respect to the X-ray contours. Clearly, the relation between the location and orbit of this galaxy with respect to the ICM is not straight forward.

Figure 3 illustrates that ram-pressure stripping is not the only physical process to remove cold gas from a galaxy. The galaxies N4026 and N4111 are among the brightest

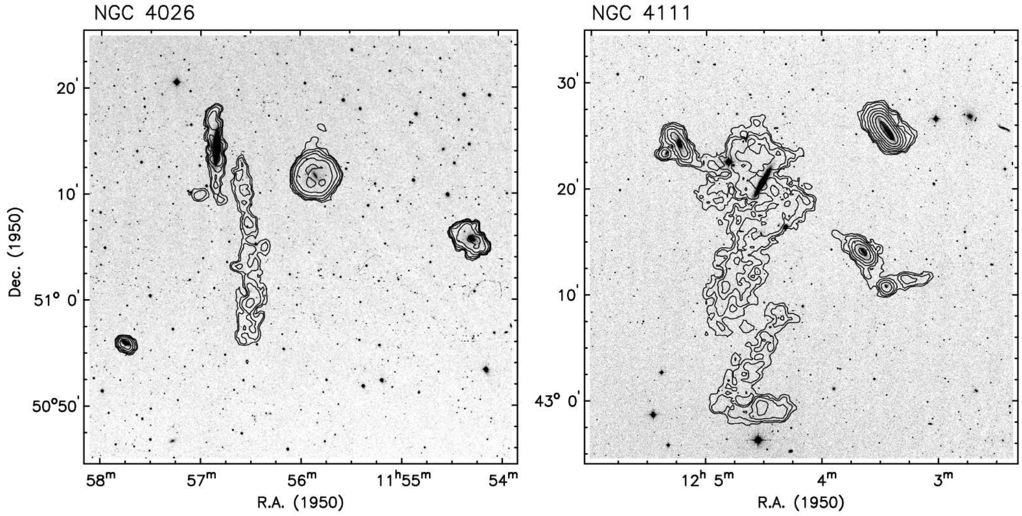

Figure 3. HI filaments observed near the brightest lenticular galaxies in the Ursa Major cluster. These lenticulars are located in small sub-groups within the Ursa Major volume.

lenticulars in the Ursa Major cluster. This dynamically young cluster has a low velocity dispersion, lacks a central concentration, shows no X-ray emission from a hot ICM, contains maybe one elliptical galaxy and a dozen lenticulars. It is an entirely different environment than the Virgo cluster. The three brightests lenticular galaxies are located in small subclumps within the Ursa Major volume, and all three (including N3998) show extended HI filaments. The orientation and kinematics of these filaments suggest that they were tidally stripped from the outer disks by their nearby companions. Do we witness here the transformation of a late-type spiral galaxy into a lenticular galaxy through tidal stripping, or the accretion of cold gas from the Inter-Galactic Medium (IGM)? Detailed modelling is required to answer this question. However, these lenticular galaxies support the notion that significant pre-processing of the cold gas component of galaxies may already occur in the lower density filaments before infalling galaxy are confronted with the higher density environment of the cluster outskirts.

Another intriguing observation, not illustrated here, is that the HI Mass Function (HIMF) may depend significantly on the environment. A most striking result is that the slope of the HIMF as observed from the HI Parkes All Sky Survey (HIPASS, Zwaan *et al.* 2003) is much steeper (~ -1.3) than what is observed both in the Local Group (Zwaan & Briggs 2000) and in the Ursa Major cluster where a flat HIMF slope (~ -1.0) is observed (Verheijen *et al.* 2001). Furthermore, the HIPASS survey suggests there is a morphological dependence of the HIMF, which is not too surprising.

5. Abell 2192: pushing the HI redshift frontier.

In an effort to include a rich galaxy cluster with a clearly observed Butcher-Oemler effect, several massive clusters near a redshift of 0.2 were selected for HI synthesis observations (see Table 1). This is the highest redshift accessible, requiring long integration times, and currently, only pilot studies have been performed to characterize feasibility and telescope performance. To be able to address issues related to selection effects, it was decided to observe a less massive and more diffuse cluster around z=0.2 as well; Abell 2192. Extensive wide-field optical imaging and multi-object spectroscopy has been ob-

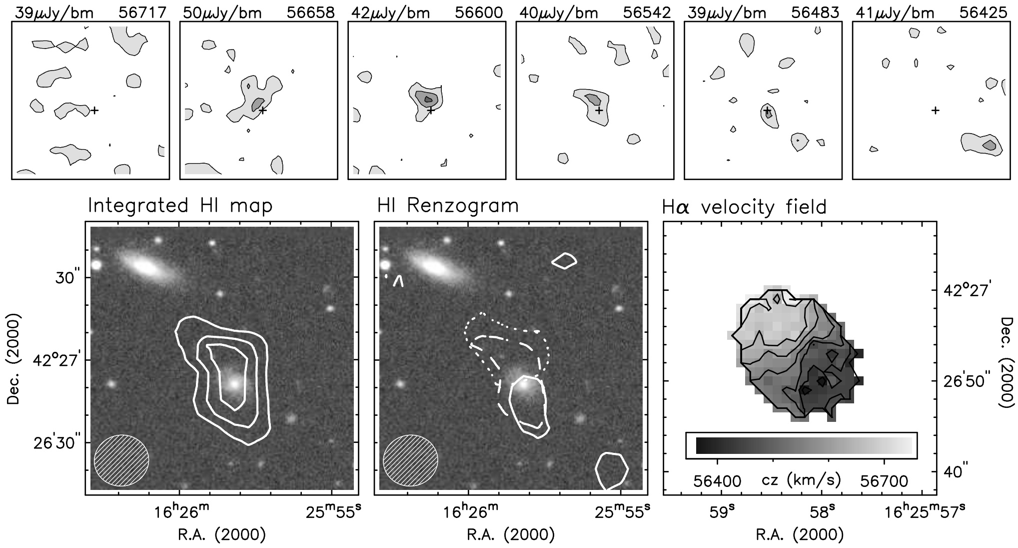

Figure 4. Atomic Hydrogen detected in Abell 2192 at z=0.1887. **Upper panels:** individual channel maps from the VLA datacube. The rms noise and Heliocentric velocity are noted above above each panel. **Lower left:** Total HI map. The contours coincide with the position of an inclined barred late-type galaxy. $M_{HI} = 7 \times 10^9 M_\odot$, SFR<12 $M_\odot$/yr. **Lower middle:** contours from the three channel maps plotted on top of eachother; solid: cz=56483 km/s, dashed: cz=56542 kms, dotted: cz=56600 km/s. **Lower left:** Hα velocity field of the optical counterpart obtained with the PMAS IFU spectrograph at the 3.5m telescope on Calar Alto. There is excellent correspondce between the HI and Hα recession velocities, confirming the HI detection.

tained for this cluster. As a feasibility study, A2192 has been observed with the VLA for ∼80 hours, and the resulting data cube contained at least one HI detection as illustrated in Figure 4. It concerns a regular inclined barred spiral galaxy at a redshift of 0.1887, located some 15′ or a projected 2.8 Mpc from the cluster center. This galaxy is part of the large scale structure around A2192. The HI data seem to suggest a possible tidal interaction with a bright and somewhat lopsided nearby galaxy of yet unknown redshift, just to the northeast. This highest redshift HI emission detected to date, demonstrates that HI imaging of Butcher-Oemler clusters at z=0.2 is feasible with present day facilities.

6. Conclusions and future plans.

Spatially resolved HI synthesis imaging of galaxy clusters provides crucial insights in the physical processes that trigger and govern the evolution and transformation of galaxies in the outskirts of clusters. Spatially resolved data have given physical meaning to HI deficiencies. The HI morphologies and kinematics of infalling galaxies help to distinguish ICM-ISM interactions from gravitational disturbances which are otherwise undetectable. The cold gas reservoir is a measure of the potential for star formation in a galaxy, and a close relation is expected between a galaxy's gas content and the evolutionary state of its stellar population, i.e. starburst, e(a), post-starburst, or passive. The radio continuum data provide dust-free measures of star formation rates. Furthermore, volume limited HI surveys of galaxy clusters help to determine the dynamical state of a cluster, and illustrates the dynamics of cluster mass accretion.

Feasibility studies for future HI imaging of Butcher-Oemler clusters at z∼0.2 have yielded the highest redshift HI emission detected to date at a redshift of 0.1887 in A2192.

Future plans entail the homogenization of the HI data sets for the various clusters listed in Table 1 in terms of volume and sensitivity. The continuation of collecting optical wide-field imaging and spectroscopy necessary to measure the blue galaxy fractions and to determine the evolutionary states of stellar populations in cluster galaxies. A new volume limited survey of the Hercules supercluster is planned in conjunction with wide-field OmegaCam imaging and other supporting observations.

Finally, the planned Square Kilometer Array (SKA) will allow us to measure the content, morphology, and kinematics of neutral Hydrogen in galaxies beyond a redshift of 1. This will revolutionize our understanding of the physical processes that shape the galaxies and determine their evolution in every imaginable environment.

Acknowledgements

The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc. The Westerbork Synthesis Radio Telescope is operated by the ASTRON (Netherlands Foundation for Research in Astronomy) with support from the Netherlands Foundation for Scientific Research (NWO). PPak is developed within the ULTROS project under the German Verbundforschung grant 05AE2BAA/4. The author wishes to thank the Scientific Organizing Committee for their invitation and travel support.

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