GAS STRIPPING IN CLUSTERS

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and the BUDHIES and WINGS collaborations
ATOMIC GAS:
A KEY INGREDIENT TO UNDERSTAND GALAXY EVOLUTION

Fuel for star formation

Sensitive tracer of different environmental processes, such as ram pressure stripping and tidal interactions, but also harassment and eventual preprocessing in infalling groups

Observations have shown that the HI gas is disturbed and eventually truncated and exhausted in galaxies in low-z clusters
BUDHIES: Blind Ultra-deep Distant HI Environmental Survey

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BLIND ULTRA DEEP HI ENVIRONMENTAL SURVEY

BUDHIES

HI ultradeep survey of ~2400hrs with Westerbork Synthesis Radio telescope in and around two clusters at z~0.2, A963 and A2192

Effective volume depth of 328 Mpc, a coverage on the sky of ~12 X 12 Mpc
**BUDHIES:** Blind Ultra-deep Distant HI Environmental Survey with the Westerbork Synthesis Radio Telescope

The clusters themselves only occupy \( \sim 4\% \) of the surveyed volumes.

Combined volume: \( 7 \times 10^4 \text{ Mpc}^3 \)

Redshift range: \( 0.15 \text{ to } 0.25 \)
BLIND ULTRA DEEP HI ENVIRONMENTAL SURVEY
BUDHIES

127 HI detections in A963 and 36 in A2192 M_HI >= 2 X 10^9 Msun

Ancillary data: WHT and WIYN spectroscopy, B+R imaging INT, NUV +FUV Galex, Spitzer imaging

GOAL: where, how and why star-forming late-type galaxies get transformed into passive early-types

Uniqueness of this study: a) very large volume sampling clusters and all the large scale structure around them, sampling all environments; b) first direct imaging study of neutral hydrogen gas at a redshift when evolutionary effects start to show
Jaffe’ et al.

GAS RESERVOIRS AND STAR FORMATION IN A FORMING GALAXY CLUSTER AT $z \sim 0.2$


BUDHIES I: characterizing the environments in and around two clusters at $z \sim 0.2$

MNRAS 431, 2111, 2013

BUDHIES II: A phase-space view of gas stripping and galaxy quenching in a cluster at $z \sim 0.2$

Submitted, 2014

See also pilot study in Verheijen+ 2007
A2192: $z=0.1876$, intermediate-mass cluster, $\sigma=530$ km/s, $L_X = 7 \times 10^{43}$ erg/s, dynamical mass $= 1.6 \times 10^{14}$ Msun, weak X-ray

A963: $z=0.2039$, $\sigma=993$ km/s, dynamical mass $1.1 \times 10^{15}$ Msun, regular and centrally concentrated in X-ray and weak lensing,
Four distinct structures, all within turnaround radius
--- main cluster, Gaussian, virialized, least HI-rich (2%), but
28% with OII emission
--- rich ensemble of “field” galaxies, very dispersed in
space, not bound – late-types: 40% with HI, 80% with OII
--- not bound, “field” spatially segregated structure, HI-rich
--- compact galaxy group, 161 km/s, 6.3 X 10^12 Msun,
mainly late-types: 63% OII, ~15% HI in the outskirts
 (>1R200) – intermediate between “cluster” and “field”
The main cluster is practically devoid of galaxies with $M_{\text{HI}} \geq 2 \times 10^9$ M$_\odot$, has suppressed star formation, and a core of red early-type galaxies that coincides with the X-ray center.

Surrounded by a scattered “field” of mostly late-type galaxies that are actively star-forming and preserve their HI reservoir.

Moreover, there is a spatially segregated compact group where galaxies show signs of pre-processing: effects on HI start to kick in in low-mass groups.
ON TO A963: RAM PRESSURE AT WORK

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**A963**

- Optical redshifts
- HI detected

**A963_1**

**A963_2**

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**A963_1**

- HI-detections
- Mass cut
- Spec. mag. limit

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**A963_2**

- UV magnitudes
- Optical magnitudes

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**Left:**

- Colour-magnitude diagrams (CMDs)

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**Right:**

- Stellar masses
- HI masses

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**Figure 2:**

- Blue galaxies (blue), lie below the red sequence fit (dotted and solid lines). The blue cloud is shown in Figure 2. We show the mass cut roughly matches the magnitude cut in some of the analysis presented in this paper. This mass cut is used to define a mass-limited sample, adopted in the spectroscopic campaign is indicated as shown by a Dressler-Shectman test (Dressler & Shectman, 1987). To distinguish different galaxy populations, we further define the blue cloud to contain all galaxies defined in the left panel, and dotted lines separating regions.
Fig. 3.— The observed PPS for all galaxies in A963. Massive galaxies ($M > 10^{10} M_\odot$) are represented with darker and larger filled symbols, HI-detected galaxies are enclosed by a blue open circle, and the grey contours follow the number density of the galaxies. The dashed black line corresponds to the escape velocity in a NFW halo (see text for details). The solid purple line delimits the region (right of the line) containing the vast majority of the HI-detections in both clusters.

Further normalized $v$ to the velocity dispersion of A963. Galaxies inside the caustic line are expected to be gravitationally bound to the cluster. The "virialized" region of the cluster is roughly located at $r \lesssim R_{200}$ and $\Delta v < 1.5 \sigma$ (see e.g. Mahajan et al. 2011), although the shape of the virialized region is best approximated by a triangle, rather than a square (as will be shown in Figures 6 and 8). Inside this region, a significant fraction of galaxies will have passed pericentre more than once. The crossing time of our clusters (from $r = R_{200}$ to the other side of the cluster) is $\sim 4$ Gyr, so the virialized region contains galaxies that have most likely been in the cluster for more than a percentric passage ($\gg 2$ Gyr).

In the PPS of Figure 3, we have distinguished low-mass galaxies from more massive ones with symbol sizes, and we can see that low- and high-mass galaxies are roughly evenly distributed across PPS in the cluster (although there are regions notably dominated by massive galaxies, such as $0.3 < r/R_{200} < 1$ and $|\Delta v|/\sigma \lesssim 0.7$). Although we always plot all galaxies for completeness, it is important to be aware that a significant assessment of the incidence of different galaxy populations can only be done in a mass-limited (or spectroscopically complete) sample. For this reason we mostly focus on the high-mass galaxies, plotted with bigger symbols in our analysis. In Figure 3 we also highlight, for the moment, HI-detected galaxies (blue squares), as these observations are the core of the survey. Later, in Figures 6 and 8 we will see how other galaxy properties are distributed in PPS. It is clear that the HI-detected galaxies are located outside the clusters' virialized regions, and that there is also a notable lack of HI-detections outside the virialized regions, at high velocities and small radii. We indicate with the solid purple line in Figure 3 the boundary between the HI-rich region (right of the line) and the HI-poor region (left of the line).

Grey contours = galaxy number density distribution
Dashed line: escape velocity in a NFW halo, projected
Solid line delimits the region where the vast majority of HI detections are

What is removing the gas in galaxies in the red region?
6.1. HI stripping in PPS

We first focus on the distribution of HI-detected galaxies (blue open squares), that notably avoid the region to the left of the dashed lines. As shown in Section 5, this area coincides with the simulation's predicted location in PPS of stripped galaxies. Our results clearly reflect how galaxies infalling into the cluster for the first time, will increase their velocities as they approach the cluster centre, and eventually cross the dashed green line of Figure 6 for the first time. This, on average, is the region to the left of the dashed lines representing the area in PPS where most galaxies are considered to be “virialized”, or at least not on their first infall. Both of these regions are mostly devoid of HI-detections, which coincides with the region where simulated galaxies that have been stripped of their gas are located in PPS, regardless of their time since infall (Figure 5). To the right of these dashed lines we have the region where galaxies that recently joined the cluster are located. This is full of HI-detections.

Dashed grey line: to the left of which MW-like galaxies are expected to be completely stripped of HI gas.

Solid green where galaxies are stripped enough to fall below our HI detection limit.

These are effects on first infall galaxies.

“Virialized region roughly at r<R200 and Av<1.5sigma, where many of the galaxies have passed pericenter more than once, thus have been in the cluster for > 2 Gyr.
We follow the orbits of individual haloes in the cluster, and apply our ram pressure model to further study the regions in PPS where galaxies have been in the "stripping region" of the diagram.

Top: only haloes that are infalling for the first time
Middle: as cluster evolves and becomes virialized, galaxies end up at low r and low v for dynamical friction -- so galaxies in this region are stripped because they are virialized, and have been in the cluster for more than a pericentric passage (> 2 Gyr) -- they have already been in the "stripping region" of the diagram
Bottom, only for MW-like galaxies (subsampling our haloes)
only a few of the blue galaxies in the stripped and virialized zones have HI, while most of the blue galaxies in the recent infall zone are detected in HI.

Also, noticeable fraction of red HI poor galaxies in the recent infall zone, possibilities:

---- preprocessing

---- wide scatter in ram pressure strength at fixed radius, non-smooth ICM

---- backsplash galaxies, but insignificant at r > 2 R200

---- “mass-quenching”? (discussing with Kovac...
BUDHIES TAKE-AWAY MESSAGES

- In the forming cluster A2192 we see effect of gas stripping both in the main virialized cluster and in a compact infalling group

- In the massive A963 cluster, we have investigated the cause and the timescale of gas stripping and subsequent quenching

  - Clear segregation of HI-stripped and non-stripped galaxies, with HI-detected galaxies avoiding the regions they “should avoid” based on ram pressure model + cosmological N-body simulations – combination of stripping on first infall + getting virialized due to dynamical friction

  - Trends of other properties (colors, OII) also segregate, but less clearly than the HI, consistent with galaxies losing their HI and having still blue colors for a while (did not show NUV colors analysis)

  - Presence of quenched, HI-poor galaxies in the infall region might indicate preprocessing, or some backsplashing
Wide-field Nearby Galaxy-cluster Survey

WINGS

A wide-field survey of 77 X-ray selected clusters at z=0.04-0.07

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THE WINGS DATASET

Sigma=500-1200+km/s, Log $L_X$=43.3-44.7 erg/s

B and V deep photometry on 34’X34’

- FOV 1.2-2.7Mpc, res. 0.7-1.6kpc, $M_V$$^\sim$-13
- 400,000 gal phot., 40,000 surf.phot + morph

Optical fibre spectroscopy

- 48 clusters, 6500 spectra, 100-200 galaxies/cluster, down to $M_V$$^\sim$-17

Near-IR deep photometry, J and K

- 36 clusters – galaxy masses, SED + struct.props

u, V and B on a 1deg sq. with Omegacam/VST +
AAOmega/AAT spectroscopic follow-up – out to 2.5
virial radii, 90% spectr. completeness to V=20, 30k
spectra

- Ongoing -

U-band with INT, LBT & Bok

Large effort: 114 telescope nights, 28 refereed pubs so far, all wide-field – ALL PUBLIC on VO
(Moretti+ 2014)

WFC/INT, WFC/ESO2.2, WYFFOS/WHT, 2dF/AAT, WFCAM/UKIRT, 90prime/Bok, LBC/LBT, Omegacam/VST, AAOmega/AAT, GMOS/
Gemini, VIMOS/VLT
6 examples from Ebeling+ 2014 in X-ray clusters at $z=0.3-0.4$

Figure 1. HST images of extreme cases of ram-pressure stripping in galaxy clusters at $z > 0.2$. From left to right: galaxy C153 in A2125 at $z = 0.20$ (WFPC2, F606W+F814W, Owen et al. 2006); galaxy 234144−260358 in A2667 at $z = 0.23$ (ACS, F450W+F606W+F814W, Cortese et al. 2007); galaxy P0083 in A2744 at $z = 0.31$ (ACS, F435W+F606W+F814W, Owers et al. 2012).

4 galaxies in merging cluster
Abell 2744   Owers+ 12

Also Rawle’s poster, Shass etc
~300 candidates of jellyfishes in 44 clusters

Some clusters have none, some have many: study vs. cluster properties

Phase-space study + position wrt Chandra maps/substructure and stellar population analysis:

---- detailed spectrophotometric modeling of fibre spectra
---- color maps (uBV) to see spatial distribution of star formation
---- IFU data pilot study in next semester

Not only in main WINGS cluster.....
2/3 of stars in clusters formed at z \geq 2, while more than half of stars in the field formed at z < 2.
FROM BLUE STAR-FORMING TO RED PASSIVE: GALAXIES IN TRANSITION IN DIFFERENT ENVIRONMENTS

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ABSTRACT

This paper presents a study of galaxy transformations in different environments utilizing a mass-complete sample drawn from the Padova Millennium Galaxy Catalogue (PMGC). We define three classes of galaxies: blue star-forming (blue), green (ellipticals and S0s), and red passive (red). The analysis is performed in low, moderate, and high density environments.

We show that blue galaxies are more numerous in low density environments, while red galaxies are more numerous in high density environments. Green galaxies are found in all environments, but their number decreases with increasing density.

We also find that blue galaxies are more likely to turn into green galaxies in high density environments, while red galaxies are more likely to turn into green galaxies in low density environments.

Finally, we show that the transformation from blue to red galaxies is more likely to occur in groups than in the field.

Keywords: galaxies, transformations, environments, PMGC, blue, green, red.