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

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ABSTRACT

We present first results from the Blind Ultra-Deep H I Environmental Survey of the Westerbork Synthesis Radio Telescope. Our survey is the first direct imaging study of neutral atomic hydrogen gas in galaxies at a redshift where evolutionary processes begin to show. In this Letter we investigate star formation, H I content, and galaxy morphology, as a function of environment in Abell 2192 (at $z = 0.1876$). Using a three-dimensional visualization technique, we find that Abell 2192 is a cluster in the process of forming, with significant substructure in it. We distinguish four structures that are separated in redshift and/or space. The richest structure is the baby cluster itself, with a core of elliptical galaxies that coincides with (weak) X-ray emission, almost no H I detections, and suppressed star formation. Surrounding the cluster, we find a compact group where galaxies pre-process before falling into the cluster, and a scattered population of “field-like” galaxies showing more star formation and H I detections. This cluster proves to be an excellent laboratory to understand the fate of the H I gas in the framework of galaxy evolution. We clearly see that the H I gas and the star formation correlate with morphology and environment at $z \sim 0.2$. In particular, the fraction of H I detections is significantly affected by the environment. The effect starts to kick in in low-mass groups that pre-process the galaxies before they enter the cluster. Our results suggest that by the time the group galaxies fall into the cluster, they are already devoid of H I.

Key words: galaxies: clusters: general – galaxies: clusters: individual (Abell 2192) – galaxies: evolution

Online-only material: color figure, animation

1. INTRODUCTION

It has been established that the shaping of galaxies, as well as their star formation activity, strongly depends on their environment (e.g., Dressler 1980). Recent large surveys (SDSS, 2dF; Lewis et al. 2002; Gómez et al. 2003) and studies of galaxy groups, cluster outskirts, and filaments (e.g., Treu et al. 2003; Wilman et al. 2009; Fadda et al. 2008; Porter et al. 2008) have further shown that the environmental dependencies extend to lower density environments, and have suggested that galaxies may be “pre-processed” before they fall into clusters. Clusters of galaxies, in relation to the large-scale structure in which they are embedded, thus offer a unique laboratory to study the effects of environments on the properties of their constituent galaxies.

The evolution of galaxy properties in clusters is strong even in the last few Gyr: the fraction of blue galaxies was higher in the past (Butcher–Oemler effect; Butcher & Oemler 1978), and the relative number of S0 galaxies increases with time, at the expense of the spiral population (Dressler et al. 1997; Fasano et al. 2000). Similar trends are also found in the field (Bell 2007; Oesch et al. 2010), where the relative number of red, passively evolving, early-type galaxies increases with time.

Much work has been done to understand the physical processes driving galaxy evolution, at low and high redshift, and at many wavelengths. In particular, H I in and around galaxies is a very useful tool for understanding galaxy formation and evolution, as it is the key ingredient for forming stars, and a sensitive tracer of environmental processes. Observations (e.g., Cayatte et al. 1990; Bravo-Alfaro et al. 2000, 2001; Poggianti & van Gorkom 2001; Kenney et al. 2004; Crowl et al. 2005; Chung et al. 2007, 2009; Abramson et al. 2011; Scott et al. 2010, 2012) have shown with impressive amount of detail that the H I gas in galaxies is disturbed and eventually truncated and exhausted in

clusters, and simulations (see Roediger 2009, for a review) have suggested that this happens via ram pressure stripping and gravitational interactions (e.g., Vollmer 2003; Tonnesen & Bryan 2009; Kapferer et al. 2009). However, due to technological limitations, studies of the H I content in galaxies have so far mostly been carried out in the local universe.

To address the questions of where, how, and why star-forming spiral galaxies get transformed into passive early-type galaxies, we have embarked on a Blind Ultra-Deep H I Environmental Survey (BUDHIES) with the Westerbork Synthesis Radio Telescope (WSRT). We refer to Verheijen et al. (2007) for technical details on the H I survey. The strategy has been to study in detail two galaxy clusters, at $z \simeq 0.2$ and the large-scale structure in which they are embedded. The unique aspect of our study is that, for the first time, we have accurate measurements of the H I content in galaxies in different environments at intermediate redshift.

Our study is the first where optical properties and gas content are combined at a redshift where evolutionary effects begin to show, and in a volume large enough to sample all environments, ranging from voids to cluster cores.

The surveyed clusters, Abell 2192 and 963 (A2192 and A963 hereafter), are very distinct. A2192, at $z = 0.188$, is less massive and more diffuse than A963. In this Letter we present first results on the effect of environment on the incidence of star-forming and H I-detected galaxies in A2192. The complete analysis of the two clusters and the large-scale structure around them will be presented in a series of papers.

2. DATA

BUDHIES is a deep H I survey of galaxies in two clusters at $0.16 \leq z \leq 0.22$ and the large-scale structure around them,

with an effective volume depth of 328 Mpc and a coverage on the sky of $\sim 12 \times 12$ Mpc that allow us to study the large-scale structure around the two Abell clusters. This campaign was possible thanks to a new back end and the low system temperature of the WSRT. The results of a pilot study are presented in Verheijen et al. (2007). The complete survey detected 118 galaxies in A963 and 42 in A2192, with H I mass $M_{\text{H I}} \gtrsim 2 \times 10^9 M_{\odot}$ (5σ) assuming a typical width of 100 km s^{-1} .

Additionally, we have obtained *B*- and *R*-band imaging with the Isaac Newton Telescope, from which we obtained photometry and morphologies. We visually classified the galaxies into early (elliptical and S0) and late types (spiral, irregular, or interacting). We also computed stellar masses from the available Sloan Digital Sky Survey (SDSS) photometry, using the method described in Zibetti et al. (2009), and a Kroupa initial mass function (see Y. L. Jaffé et al. 2012, in preparation). Furthermore, we acquired deep NUV and FUV imaging with the *Galaxy Evolution Explorer* (M. Montero-Castaño et al. 2012, in preparation), as well as other auxiliary data that will be presented in future papers.

A few redshifts are available from the literature and the H I observations in the field of A2192 (15 from SDSS, 44 spectra taken with WIYN/Hydra in the redshift range of the H I observations, and 42 from WSRT).

In order to study the clusters and the large-scale structure around them, we obtained additional optical spectroscopy for galaxies in and around our clusters using AutoFib2+WYFFOS (AF2), the multi-object, wide-field, fiber spectrograph mounted at the William Herschel Telescope (WHT). The spectroscopy is thoroughly described in Y. L. Jaffé et al. (2012, in preparation). In short, we targeted galaxies with colors consistent with the red sequence and blue cloud at the cluster redshift, down to $R = 19.4$ ($R = 20.4$ for H I-detected galaxies). The optical AF2/WYFFOS WHT spectroscopy was reduced with the new AF2 data-reduction pipeline.

The AF2/WHT spectroscopy yielded 377 new redshifts in A2192. Redshifts were measured from emission lines when possible (mostly [O II]) and from absorption lines (typically Ca H and K).

We also measured rest-frame equivalent widths (EW) of the [O II] 3727 Å line, which we used as a proxy for ongoing star formation: we considered galaxies as “star forming” if $\text{EW}[\text{O II}] \geq 4 \text{ \AA}$ in emission. We applied the same method to the WIYN spectra. For galaxies with only SDSS spectra, we used $\text{EW}[\text{O II}] = \text{EW}[\text{O II}]_{3726} + \text{EW}[\text{O II}]_{3729}$ from DR7.

3. RESULTS

3.1. Defining Environment

Figure 1 shows the redshift distribution of the galaxies in A2192. There is one main structure centered at $z = 0.1876$ (A2192_1, red solid histogram) with a large number of galaxies (101), and several foreground and background galaxy clusters/groups (gray histograms) that will be fully studied in Y. L. Jaffé et al. (2012, in preparation). In this Letter, we will focus on A2192_1.

The cluster velocity dispersion (σ_{cl}) and central redshift (z_c) were computed following Beers et al. (1990) and are listed in Table 1. We considered cluster members those galaxies with radial velocities within 3σ from z_c . From σ_{cl} , we also calculated R_{200} , the radius delimiting a sphere that has mean enclosed density equal to 200 times the critical density.

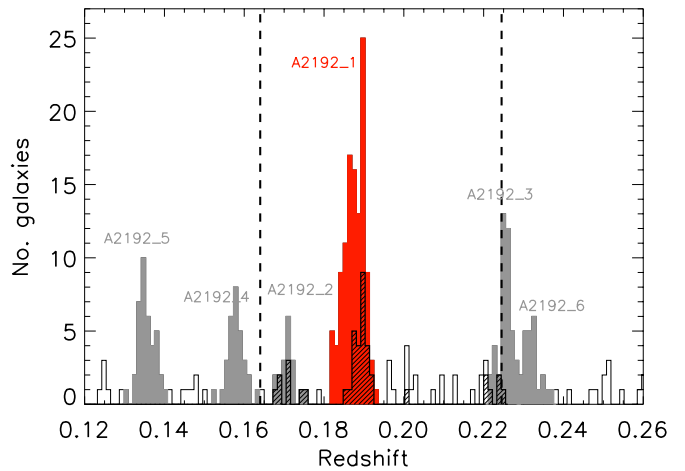


Figure 1. Redshift distribution for galaxies in A2192. Redshifts are mainly taken from the WHT observations, although we also include redshifts from SDSS, WIYN, and WSRT observations. Only secure redshifts were used to construct this histogram and characterize the structures. The focus of this Letter is the main cluster at $z = 0.1876$ (A2192_1, red histogram). However, additional groups of galaxies are also identified in the plot in filled gray histograms for future reference. The vertical dashed lines delimit the redshift range of the H I observations, and the filled-dashed histogram shows the distribution of the H I-detected galaxies.

(A color version of this figure is available in the online journal.)

From the histogram of Figure 1, it is hinted that A2192_1’s redshift distribution is not entirely Gaussian. This is shown more clearly on the top panel of Figure 3, where only the galaxies in A2192_1 are plotted (open black histogram). The distribution shows a double-peak shape, strongly suggesting that this “cluster” is not virialized, and contains significant substructure.

To identify the substructures inside A2192_1, we combined the redshift information with the distribution of galaxies on the sky. This yielded a three-dimensional (3D) picture, in which it becomes evident that the cluster indeed has four distinct substructures. These are illustrated in Figure 2, where the different substructures are represented with different colors. Figure 2 shows a reduced number of galaxies as a consequence of limiting the plotted sample to galaxies with optical spectroscopy (and thus $\text{EW}[\text{O II}]$ measurements), and keeping our spectroscopic magnitude limit ($R \leq 19.4$ mag, i.e., excluding the faintest H I galaxies). Such “reduced sample” is defined to compare the fraction of star-forming galaxies with the fraction of H I galaxies within the structures (see Section 3.2). Substructures within A2192_1 were identified on the basis of all galaxies with a reliable redshift, although not all these galaxies are shown in Figure 2 for clarity. We note that we identified these structures without using any information on galaxy morphology, H I content, or [O II] emission. We identified them only by carefully inspecting the 3D distribution of the galaxies searching for galaxy groups separated in redshift and/or space.

The different substructures are also presented in the redshift histogram at the top of Figure 3. We named these substructures A2192_1a (red in Figure 2 and the upper panel of Figure 3), A2192_1b (gray), A2192_1c (turquoise), and A2192_1d (yellow). The properties of the structures are listed in Table 1 and discussed in Section 3.2.

3.2. H I, Star Formation, Morphology, and Stellar Mass as a Function of Environment

Figure 2 shows detections of H I and star formation activity, as well as morphology of the galaxies in each of the structures

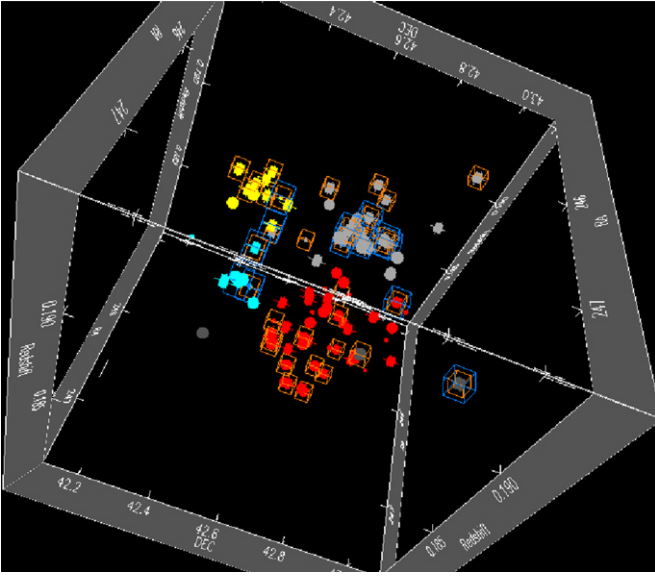


Figure 2. 3D (α - δ -redshift) visualization of galaxies in A2192_1 (made with the S2PLOT programming library; Barnes et al. 2006). The galaxies are color coded according to the substructure they belong to: red corresponds to A2192_1a, light gray to A2192_1b, turquoise to A2192_1c, and yellow to A2192_1d, as in Figure 3 (darker gray represents galaxies not associated with any of the mentioned structures). H I-detected galaxies are surrounded by blue open cubes, while star-forming galaxies are surrounded by (smaller) open orange cubes. Morphology is illustrated with different symbols: big spheres correspond to early-type galaxies, solid cubes with spikes are late types, and small symbols are galaxies with undetermined morphology. Only galaxies in the “reduced sample” are used. The α - δ plane is $\cong 14 \times 14$ Mpc. The white segment indicates 1 Mpc at the cluster redshift.

(An animation of this figure is available in the online journal.)

in A2192_1. The bottom panel of Figure 3 further shows the redshift distribution of the galaxies in A2192_1 (black open histogram), with additional histograms for H I-detected (blue) and star-forming (orange) galaxies. Interestingly, the H I

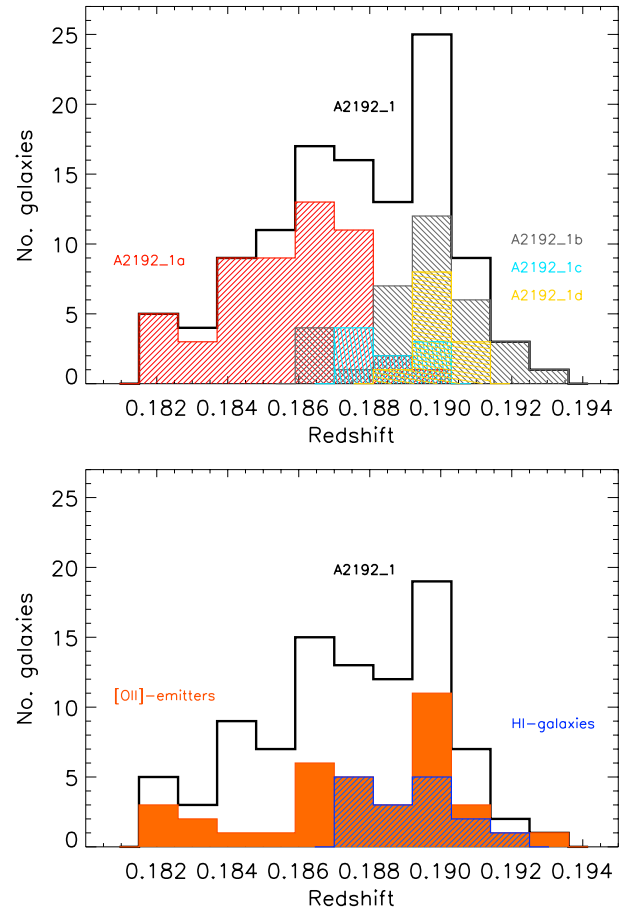


Figure 3. Top: the overall redshift distribution of the galaxies in A2192_1 (open black histogram), and the four substructures found within A2192_1 in colored filled-dashed histograms (same colors as in Figure 2). Bottom: the redshift distribution of A2192_1 galaxies is shown, in addition to the distribution of the H I-detected galaxies (blue filled-dashed histogram), and the galaxies with [O II] emission (solid dark orange histogram). In the top plot we use all galaxies in A2192_1, and in the bottom plot we use the “reduced sample.”

Table 1
Characteristics of A2192_1 and Its Composing Substructures (see Figures 2 and 3)

Name of Structure	z_c	No. Members	Frac. H I Galaxies	Frac. [O II] Emitters	Frac. LTGs with H I	Frac. LTGs with [O II]	σ_{cl} (km s $^{-1}$)	R_{200} (Mpc)	Remarks (and Color in Figures)
A2192_1	0.1876	101 (93)	14 $^{+4}_{-3}$ % (13/93)	39 \pm 5% (36/93)	21 $^{+7}_{-5}$ % (10/48)	56 \pm 7% (27/48)	653 \pm 62	1.43	Central “cluster” in A2192 (red histogram in Figure 1)
A2192_1a ^a	0.1859	50 (46)	2 $^{+5}_{-1}$ % (1/46)	28 $^{+7}_{-6}$ % (13/46)	5 $^{+9}_{-1}$ % (1/22)	36 $^{+11}_{-9}$ % (8/22)	530 \pm 56	1.16	Richest and more massive substructure in A2192_1 (red in top panel of Figures 2 and 3)
A2192_1b	0.1898	29 (25)	24 $^{+10}_{-6}$ % (6/25)	52 $^{+9}_{-10}$ % (13/25)	40 $^{+13}_{-11}$ % (6/15)	80 $^{+7}_{-14}$ % (12/15)	–	–	Disperse, “field-like” (gray)
A2192_1c ^b	0.1881	8 (8)	38 $^{+18}_{-13}$ % (3/8)	25 $^{+19}_{-9}$ % (2/8)	50 \pm 25% (1/2)	50 \pm 25% (1/2)	–	–	Poor, disperse (turquoise)
A2192_1d ^{a,b}	0.1902	11 (11)	18 $^{+16}_{-6}$ % (2/11)	55 $^{+13}_{-15}$ % (6/11)	13 $^{+20}_{-5}$ % (1/8)	63 $^{+13}_{-18}$ % (5/8)	161 \pm 52 ^a	0.35	Small, compact group (yellow)

Notes. The columns are: name of cluster/structure, median redshift (z_c), number of galaxies ($R \leq 19.4$), fraction of H I-detected galaxies, fraction of galaxies with $EW[\text{O II}] \geq 4 \text{ \AA}$, fraction of late-type galaxies with H I emission, fraction of late-type galaxies with $EW[\text{O II}] \geq 4 \text{ \AA}$, cluster/group velocity dispersion, R_{200} (“–” is placed when it is not applicable), comments. The numbers inside parenthesis at the bottom of the quoted values correspond to the “reduced sample” we used to calculate H I and O II fractions of Columns 4–7. Error on the fractions corresponds to the confidence intervals ($c \approx 0.683$) for binomial populations, from a beta distribution (see Cameron 2011).

^a The luminosity-weighted geometric centers of A2192_1a and A2192_1d are at $\alpha = 246^{\circ}64774$, $\delta = +42^{\circ}727723$, and $\alpha = 246^{\circ}48559$, $\delta = +42^{\circ}380932$, respectively.

^b Because these structures are located far from the pointing center of WSRT’s primary beam, the H I fractions suffer from beam attenuation effects (fully treated in B. Z. Deshev et al. 2012, in preparation). We estimate that the fraction of H I galaxies among the late types can increase at most by a factor of two.

detections are offset to higher redshift with respect to A2192_1a. Star-forming galaxies, on the other hand, are spread across all redshifts.

In the following we analyze the characteristics of each substructure and its galaxy population, as presented in Figure 2, to unveil the effect of environment on the galaxies’ properties.

1. *A2192_1a*. This structure is the main cluster. It is well defined in space, is the richest and most massive of all substructures, and has a nearly Gaussian redshift distribution, suggesting it is gravitationally bound and virialized. It is an intermediate-mass cluster ($2.27 \times 10^{14} M_{\odot}$, or $\sigma_{cl} = 530 \text{ km s}^{-1}$), and is clearly still assembling. Additional evidence that supports the presence of a cluster comes from the X-ray emission in A2192, which, although weak, coincides with the group of early-type galaxies at the core of A2192_1a. Moreover, the derived virial mass is consistent with the X-ray luminosity ($L_X \simeq 7 \times 10^{43} h_{100}^{-2} \text{ erg s}^{-1}$; Voges et al. 1999).

A2192_1a is the least H I-rich of the four structures. Only 1 out of 46 (2%) of the galaxies in this cluster are H I detections, and these are located at a projected distance of $\sim 2 \times R_{200}$ from the center, at the boundary of the cluster, where A2192_1a meets A2192_1b. Nonetheless, A2192_1a has a significant fraction (28%) of galaxies with [O II] emission. All of the H I-detected galaxies, as well as the majority of the star-forming galaxies are late types, as one would expect. Overall, the galaxies in this cluster, although devoid of H I, still host star formation, especially toward the outskirts.

2. *A2192_1b*. Although very rich, it is very dispersed in space. This “structure” is unlikely to be a bound group, as its shape and location are consistent with that of a population of field galaxies. The late-type galaxy population in this ensemble of “field” galaxies has 40% of H I detections and 80% of emission-line galaxies. All the H I-detected galaxies have [O II] emission, and all H I and [O II] galaxies were classified as late-type galaxies, as one could expect. However, it is interesting to note the presence of a few (8 out of 25) early-type galaxies with neither H I nor [O II] emission. It is possible that some of the early types in this group are truly field E/S0 galaxies, but it is also possible that some are early spirals that were classified as E/S0.
3. *A2192_1c*. With less than 10 galaxies, and considerably spread in space, it is unlikely to be a gravitationally bound system. Although spatially separated from the other structures, it resembles the “field” (like A2192_1b). Its galaxies span the whole morphology range, with a few more late-type galaxies than early types. The fraction of late-type galaxies detected in H I is similar to that in A2192_1b.
4. *A2192_1d*. Likely to be a galaxy group, it is very compact and clearly separated in space. Its dynamical mass is small ($6.34 \times 10^{12} M_{\odot}$, based on $\sigma_{cl} = 161 \text{ km s}^{-1}$), and it is composed mainly of late-type galaxies. Sixty-three percent of the late-type galaxies are star forming, and a few (between 13% and 26%) have H I reservoirs. All the galaxies with H I or [O II] emission are late types, while the rest are early types. As in A2192_1, the H I-detected galaxies are in the outskirts of the group (at $>1 \times R_{200}$), with the exception of one. The star formation on the other hand is more widely spread. The properties of this group place it somewhere in between the cluster (A2192_1a) and the field (A2192_1b), which suggests that it might be a place

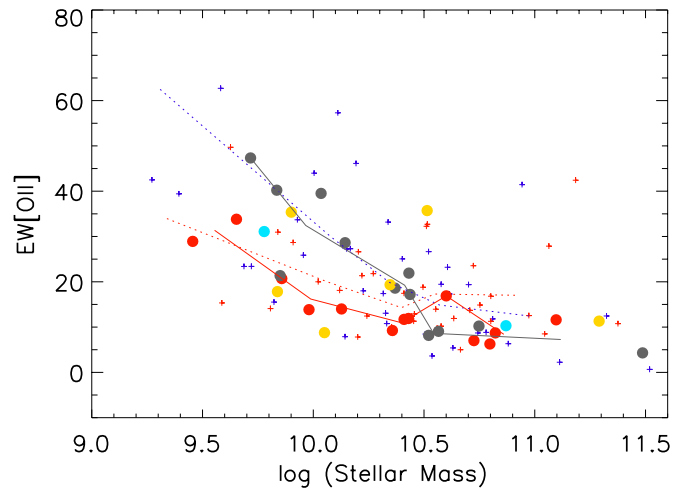


Figure 4. EW[O II] vs. stellar mass for the different structures in A2192_1 (filled circles, same colors as in Figure 2). For comparison, we also include the field population at a similar redshift (in A2192 and A963, blue crosses), and other clusters in the redshift range (same as in gray histograms of Figure 1, red crosses). Lines correspond to average EW[O II] in several mass bins for field galaxies (dotted blue), A2192_1a (solid red), A2192_1b (solid gray), and other clusters (dotted red). We adopt the same “reduced sample” of Figure 2.

where galaxies are being “pre-processed.” It is also possible that the gas gets removed from group galaxies as the groups become more compact (Verdes-Montenegro et al. 2001), or that the gas in this compact group gets removed as it moves closer to the cluster, or both.

The structures surrounding the main cluster (A2192_1a) are all at a distance well within A2192_1a’s turnover radius (cf. Rines & Diaferio 2006), implying that they will eventually be accreted by the cluster.

To assess whether the star formation rate in star-forming galaxies is reduced/suppressed by the environment, we compared the EW[O II] in each structure at fixed galaxy stellar mass. As Figure 4 shows, star-forming galaxies in A2192_1a have a suppressed star formation (i.e., lower EW[O II]) at stellar masses $\lesssim 3 \times 10^{10}$, while A2192_1b is consistent with the field population. Unfortunately, the numbers are too low to make conclusions about A2192_1c and A2192_1d. Nonetheless, (near and far) UV color–color plots reveal a clear separation of the structures (see M. Montero-Castaño et al. 2012, in preparation): A2192_1a and A2192_1d have redder (older) galaxies, when compared with A2192_1b and A2192_1c, supporting our environmental definitions.

4. SUMMARY

We have studied the fraction of star-forming and H I-detected galaxies in A2192. In B. Z. Deshev et al. (2012, in preparation) we present the ultra-deep H I survey covering $0.16 \leq z \leq 0.22$, which is the core of this study. In this Letter we present first results from combining the H I observations with optical spectroscopy and imaging. The redshift distribution reveals several structures. We focus on the central overdensity at redshift $z = 0.1876$ (A2192_1). This “cluster” shows clear signs of substructure, both in its redshift and spatial distribution. By inspecting it in 3D (α – δ – z) we identify four distinct substructures: a medium-sized galaxy cluster in the process of forming, surrounded by a less massive infalling group, and a spread population of “field-like” galaxies.

Further evidence from observed galaxy properties support the idea that the cluster is still assembling. Most notably, the

main cluster (A2192_1a) is practically devoid of galaxies with $M_{\text{H I}} \geq 2 \times 10^9 M_{\odot}$, has suppressed star formation, and a core of red early-type galaxies that coincides with the X-ray center. The cluster is surrounded by a scattered “field” (A2192_1b and A2192_1c) of mostly late-type galaxies that are actively star forming and still preserve their H I reservoirs. Moreover, there is a spatially separated compact group (A2192_1d), where galaxies show signs of being pre-processed before the group falls into A2192_1a. This suggests that the environmental effect starts to kick in in low-mass groups that pre-process the galaxies before they enter the cluster. In the case of cluster growth via group accretion, it is likely that by the time the group galaxies fall into the cluster, they are already devoid of H I.

A2192 proves to be an excellent laboratory to understand the fate of the H I gas in the framework of galaxy evolution. In particular, we clearly see that the H I gas, as well as the star formation in late-type galaxies, correlates with environment at $z \sim 0.2$. Our results suggest that the H I gas gets removed and star formation suppressed progressively, from the lowest mass galaxy groups to cluster-sized structures, as smaller structures get assembled into larger structures.

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