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

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ABSTRACT

We present the optical spectroscopy for the Blind Ultra Deep H I Environmental Survey (BUDHIES). With the Westerbork Synthesis Radio Telescope, BUDHIES has detected H I in over 150 galaxies in and around two Abell clusters at $z \approx 0.2$. With the aim of characterizing the environments of the H I-detected galaxies, we obtained multifibre spectroscopy with the William Herschel Telescope. In this paper, we describe the spectroscopic observations, report redshifts and EW[O II] measurements for $\sim 600$ galaxies, and perform an environmental analysis. In particular, we present cluster velocity dispersion measurements for five clusters and groups in the BUDHIES volume, as well as a detailed substructure analysis.

Key words: galaxies: clusters: general – galaxies: clusters: individual: Abell 963 – galaxies: clusters: individual: Abell 2192 – galaxies: evolution.

1 INTRODUCTION

Rich clusters of galaxies, in relation to the large-scale structure in which they are embedded, offer a unique laboratory to study the effects of global and local environments on the properties of their constituent galaxies. Evidence has accumulated that the star formation activity, as well as galaxy morphology strongly depend on the environment in which galaxies are located. This is well exemplified by the morphology–density relation (Dressler 1980), that shows that early-type galaxies are more frequent in regions with high local density (the number of galaxies per unit projected area, or volume), while spirals dominate the low-density regions.

The evolution of galaxy properties in clusters is strong, even in the last few Gyr: the fraction of blue galaxies in clusters was higher in the past (Butcher–Oemler B–O 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; van Dokkum et al. 1998; Fasano et al. 2000; Desai et al. 2007). Similar trends are now known to take place also in the field (Bell 2007; Oesch et al. 2010), where the relative numbers of red, passively evolving, early-type galaxies increases with time.

Recent large surveys (SDSS, 2dF: Lewis et al. 2002; Gómez et al. 2003; Haines et al. 2007; Mahajan, Raychaudhury & Pimbblet 2012) and studies of groups, cluster outskirts and filaments (e.g. Treu et al. 2003; Fadda et al. 2008; Porter et al. 2008; Wilman et al. 2009; Roychowdhury et al. 2012) have shown that the environmental dependences extend to the lowest density environments. It is now thought that galaxies may be ‘pre-processed’ before they fall into clusters, i.e. environmentally driven evolution occurs in lower density environments. A remaining question is where and how does this happen.

Furthermore, clues (or perhaps questions) come from the structure formation scenario of $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology, that predicts that many galaxies have undergone the transition from field to cluster environments since $z \lesssim 1$ (De Lucia et al. 2012). In fact, there is an ongoing debate on whether it is the cluster environment that drives galaxy evolution and transforms galaxies (nurture), the field population that accretes on to clusters and that evolves with cosmic time (nature), or both (e.g. Kauffmann et al. 1999; Poggianti et al. 1999; Ellingson et al. 2001; Kodama & Bower 2001; Desai et al. 2007; Bolzonella et al. 2010; Vulcanti et al. 2010; Jaffe et al. 2011).

A crucial tracer of galaxy evolution is the neutral atomic hydrogen gas from which the stars are formed. H I is a sensitive tracer of different environmental processes, in particular of tidal interactions and ram pressure stripping. Observational evidence (e.g. Cayatte et al. 1990; Bravo-Alfaro et al. 2000, 2001; Poggianti & van Gorkom...
inspect the clusters thoroughly for substructure in Section 5, and summarize the main characteristics of each of the identified cluster/groups in Section 6. Finally, we present our conclusions in Section 7.

Throughout this paper, we use Vega magnitudes and assume a ‘concordance’ ΛCDM cosmology with \( \Omega_M = 0.3, \Omega_\Lambda = 0.7 \) and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), unless otherwise stated.

2 THE BUDHIES PROJECT

The WSRT deep environmental survey targeted two clusters at \( z \lesssim 0.2 \), as well as the large-scale structure around them. The surveyed clusters, A2192 and A963, are very distinct. A963 at \( z = 0.206 \) is a massive lensing B–O cluster with an unusually large fraction of blue galaxies (Butcher et al. 1983), and a total X-ray luminosity of \( L_X \simeq 3.4 \pm 1 \times 10^{44} \text{ erg s}^{-1} \) (Allen et al. 2003). A2192 at \( z = 0.188 \) is a less massive cluster in the process of forming, with a high degree of substructure (Jaffé et al. 2012). It has a velocity dispersion of 653 km s\(^{-1}\) and is barely detected in X-rays (\( L_X \simeq 7 \times 10^{42} \text{ erg s}^{-1} \); Voges et al. 1999).

With the assumed cosmology, the spatial scales at the distances of A963 and A2192 are 3.4 and 3.1 kpc arcsec\(^{-1}\), respectively.

After integrating for \( 117 \times 12^h \) on A963 and \( 76 \times 12^h \) on A2192 with the WSRT, more than 150 galaxies were detected and imaged in H\(_\alpha\). The observations span a redshift range of 0.164–0.224, a luminosity distance of 0.79–1.11 Gpc, and a look-back time interval of 2.04–2.68 Gyr. The results of a pilot study are presented in Verheijen et al. (2007). In short, this recently completed 4 year long-term large programme focused on two (single-pointing) volumes, each containing an Abell cluster of galaxies, as well as fore- and background voids, sampling the broadest range of cosmic environments.

The depth of the WSRT observations allows a solid detection of a minimum H\(_\alpha\) mass of \( 2 \times 10^8 \text{ M}_\odot (5\sigma) \), assuming a typical width of 100 km s\(^{-1}\). It should be noted that the galaxy clusters only occupy \( \sim 4 \) per cent of the surveyed volumes while the entire combined volume that has been blindly surveyed with the WSRT is \( \sim 73 \times 10^6 \text{ Mpc}^3 \), equivalent to the volume of the local Universe within a distance of 26 Mpc.

In addition to the H\(_\alpha\) data, we have obtained near and far-UV imaging with GALEX (Montero-Castaño et al. in preparation); 3.6, 4.5, 5.6, 8, 24 and 70 micron imaging with Spitzer (Cyuibalski et al. in preparation); Herschel imaging (with SPIRE and PACS, Yun et al. in preparation); as well as 36 spectra with the Wisconsin Indiana Yale NOAO (WIYN) Telescope in the field of A2192. Finally, we also obtained B- and R-band imaging with the Isaac Newton Telescope (INT) in both clusters. These observations over a one square degree field were carried out under significantly better seeing conditions, and are much deeper than the available Sloan Digital Sky Survey (SDSS) photometry.

Fig. 1 shows a redshift pie diagram from available SDSS redshifts, showing the location of our surveyed clusters at \( z \simeq 0.2 \) and highlighting the depth of the H\(_\alpha\) survey. This diagram already shows overdensities at the studied redshifts but it is evident that additional spectroscopy is needed to define the structures. In addition to the SDSS and WIYN redshifts, we also have 89 redshifts in the very centre of A963 from Lavery & Henry (1994, and private communication), as well as 111 redshifts from Czoske (private communication) in the same field. However, the redshifts from Lavery & Henry (1994) were used cautiously, as they suffer from large uncertainties.
In the following section, we present optical spectroscopy of a large number of galaxies in the two volumes, obtained at the WHT.

3 OPTICAL SPECTROSCOPY

3.1 Target selection

To design the spectroscopic observations, we made use of the $B$- and $R$-band magnitudes, the astrometry, and the galaxy–star separation from the INT photometry, as well as the HI detection information and the available redshifts. Our selection and prioritization criteria are summarized in the following.

(i) Type of object: the galaxy–star separation index (as given by SExtractor) in either the $B$ or the $R$ band was $\leq 0.3$, in order to clean the sample from objects that are not galaxy-like.

(ii) Location in the colour–magnitude diagram (CMD): for each field, we created CMDs showing $R$ versus $B - R$ (see Fig. 2) for all the sources detected in the photometry that were classified as galaxies [cf. bullet point (i)]. We selected galaxies within the black solid boxes shown in the CMDs of Fig. 2 and included fainter HI-detected galaxies (up to $R = 20.5$). This was done partially to confirm clear optical counterparts of fainter HI detections. The magnitude limits for each field are listed in Table 2. Fig. 2 shows that the red sequence is well defined in both clusters. The figure also shows that the vast majority of HI-detected galaxies are located in the so-called ‘blue cloud’.

(iii) Area in the sky: although fibres can be positioned over a field of one degree diameter, we only selected galaxies inside a radius of 25 arcmin (centred on the pointings of the HI observations), as it is the radius within which vignetting is not dramatically strong. The spatial distribution of the targeted galaxies (red circles) and the field of view of the WSRT and WHT are shown in Fig. 3.

(iv) Prioritizing the fibre allocation: when allocating fibres to objects, we gave the top priority to HI-detected galaxies, lower priority to other targeted galaxies, and the lowest priority to galaxies that already had redshifts from the literature$^1$ in the range of the HI survey (see Table 1). Furthermore, when the literature redshifts were outside the cluster redshift range (open black circles in Fig. 2), we explicitly rejected the galaxies.

3.2 Observations and data reduction

The spectroscopic observations were made using the AutoFib2+Wyffos (AF2) wide-field, multifibre spectrograph mounted on the 4.2 m WHT in La Palma. AF2 contains 150 science fibres (of 1.6 arcsec diameter and 26 m in length), and 10 fiducial bundles for acquisition and guiding. At the prime focus, the fibres are placed on to a field plate by a robot positioner at user-defined sky coordinates. Object light is transmitted along the fibres to the spectrograph.

We used the R600B grating with the 2-chip EEV 4300 × 4300 mosaic that counts with 13.5 µ pixels. Using a 2 × 3 binning of the CCD pixels, we obtained a spectral resolution of $\sim 4$ Å full width at half-maximum (FWHM) (depending on the location on the CCD). The spectra were centred on a wavelength of $\sim 4900$ Å and covered the range $\sim 3900$–6900 Å. In this range, galaxies at the targeted redshift showed spectral features from the Ca H&K lines, and the [O II] line in the blue, up to NaD in the red (see Fig. 4). We used He and Ne lamp exposures for wavelength calibration.

We obtained the data in two runs (2011 April and June) during five dark nights in total. In this time, we were able to observe 12 fibre configurations, each containing $\sim 80$ galaxies. The targeted galaxies were divided into different configurations (see Table 2) depending on their luminosities: for each field, we created three bright and three faint configurations. For the bright ones, the exposure times

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$^1$ Whenever we refer to ‘literature redshifts’ we are referring to SDSS, WyIN, Larvery & Henry and Czoske (see Section 2).
Figure 2. The CMDs of A963 (left) and A2192 (right). All galaxies in the SDSS photometric catalogues and in our INT images are plotted in small grey dots. The red filled circles indicate galaxies with the literature redshifts that lie inside the H I redshift range (0.164 ≤ z ≤ 0.224), whilst the black open circles are those with the literature redshifts outside this range. The bigger blue filled circles highlight the H I-detected galaxies. The solid triangles correspond to new WHT redshifts inside the H I redshift range, and open triangles are those with WHT redshifts outside the range. In each case, the solid box delimits the region containing the galaxies targeted for spectroscopy, and the extended dashed area shows the fainter range in which only galaxies with H I detections were targeted.

Figure 3. The distribution of targeted (black points) and observed (red filled circles) galaxies in A963 (left) and A2192 (right). The black square represents the area within 68 × 68 arcmin$^2$ of the WSRT pointings. The bigger circle (30 arcmin radius) encloses the field of view of WHT, whilst the smaller dashed circle (25 arcmin radius) shows the unvignetted area.

Table 1. For each field the table lists: the number of galaxies with redshifts available from the literature in the two surveyed fields (within 0.164 ≤ z ≤ 0.224), number of H I-detected galaxies, number of galaxies targeted for WHT spectroscopy [fulfilling the criteria listed in bullet-points (i) to (iii) in Section 3.1] and number of new redshifts obtained in our spectroscopic campaign (with quality flag ≥ −1, cf. Section 3.3).

<table>
<thead>
<tr>
<th>Field</th>
<th>No. of literature z in H I range</th>
<th>No. of H I galaxies</th>
<th>No. of WHT targets</th>
<th>No. of WHT z in H I range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A963</td>
<td>161</td>
<td>119</td>
<td>853</td>
<td>261</td>
</tr>
<tr>
<td>A2192</td>
<td>67</td>
<td>37</td>
<td>612</td>
<td>251</td>
</tr>
</tbody>
</table>

were chosen to be 1 h and for the faint ones 3 h, in order to recover a signal-to-noise ratio ≳ 10, although in practice, we extended the exposure times when possible. We tried to maximize the number of fibres allocated on galaxies but also placed typically 20–30 fibres on the sky, for sky subtraction purposes.

As explained in Section 3.1, we prioritized our targets according to their H I content, and previous observations. Although we did not target the same galaxy more than once, in some cases, the software that allocates fibres to coordinates in the sky (AF2_CONFIGURE) used fibres, that could not be allocated to a new galaxy, to target galaxies previously observed in another configuration. For this reason, we have a few dozen galaxies with repeated observations (in different configurations, and sometimes in different runs), which were helpful for characterizing our redshift errors and the quality of our data.
Figure 4. Example of the extracted, calibrated and sky-subtracted spectra for a galaxy with strong [O\textsc{ii}] emission, as well as some absorption features (left) and an absorption-line galaxy (right). The wavelength (\(\lambda\)) is expressed in Å and the flux (vertical axes) in arbitrary units. The green vertical lines indicate the main lines (such as [O\textsc{ii}] emission or the Ca H&K absorption lines) from which the redshift was calculated. The measured redshift in each case is also indicated at the top-left corner of each spectra.

Table 2. Magnitude and colour limits for spectroscopic target selection. The colour cuts were applied to all samples, and the magnitude limits are those highlighted with boldface (see also the red boxes in Fig. 2). We split the galaxy sample into ‘bright’, ‘faint’ and ‘fainter H\textsc{i} galaxies’, to produce configurations of the same exposure time, and maintain the signal-to-noise ratio above 10. The bright configurations were observed for \(\geq 1\) h, whilst the faint configurations (including the fainter H\textsc{i} galaxies) were observed for \(\geq 3\) h.

<table>
<thead>
<tr>
<th>Field</th>
<th>Bright sample</th>
<th>Faint sample</th>
<th>Fainter H\textsc{i} galaxies</th>
<th>Colour constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abell 963</td>
<td>15.0 (&lt; R &lt; 18.5)</td>
<td>18.5 (&lt; R &lt; 19.5)</td>
<td>19.5 (&lt; R &lt; 21.0)</td>
<td>0.98 (&lt; B - R &lt; 2.38)</td>
</tr>
<tr>
<td>Abell 2192</td>
<td>16.0 (&lt; R &lt; 18.5)</td>
<td>18.5 (&lt; R &lt; 19.5)</td>
<td>19.5 (&lt; R &lt; 20.5)</td>
<td>0.92 (&lt; B - R &lt; 2.24)</td>
</tr>
</tbody>
</table>

The data were reduced using the new AF2 data reduction pipeline.\(^2\) We started using the pipeline before the final version was released, and hence helped testing the pipeline. Our final spectra however were reduced with the latest (final) version. To control the quality of our final reduction, we compared the final product with (a subsample of) the same spectra reduced with IRAF (using the IRAF package DOFIBER), coming to the conclusion that the pipeline performs well, and that it is significantly faster and more efficient than DOFIBER.

The pipeline is written in IDL and is able to perform full data reduction, including fibre to fibre sensitivity corrections and optimal extraction of the individual spectra. The first steps of the pipeline include master bias correction, tracing of the fibres, flat-field correction and masking of bad pixels in the science data. Twilight sky flats were used to define the apertures and trace the spectra on the CCD, and to perform the flat-field correction. An optimal extraction algorithm is used for extracting the spectra. The software accounts for wing emission from adjacent fibres.

As for the wavelength calibration, the software selects an arc lamp spectrum from a fibre near the centre of the chip. The user is then prompted to identify the principal arc lines (between 10 and 12 in our case). Other significant lines are automatically identified and then a dispersion solution is found using a polynomial fit. Once the user is satisfied, the dispersion solution is propagated to the rest of the fibres. Typically, the fits yielded an rms scatter of 0.03 Å.

Because not all fibres have the same throughput, we scaled the final spectra according to an estimation of the throughput in each fibre that the pipeline estimates from the master flat.

A master sky spectrum was also derived for each exposure by combining the spectra (using the median) of the 20–30 individual fibres assigned to the sky. The median is then subtracted from each science spectrum.

Finally, the multiple exposures in each pointing were combined (after extraction) with cosmic rays being removed.

Fig. 4 shows example reduced spectra, and Table 1 summarizes the target selection and the outcome of our spectroscopic campaign.

3.3 Galaxy redshifts and EW[O\textsc{ii}]

Spectroscopic galaxy redshifts were measured using emission lines where possible (typically the [O\textsc{ii}]3727 Å line), or the most prominent absorption lines (e.g. Ca H&K lines at 3934 Å and 3968 Å), as shown in Fig. 4. The redshifts were manually assigned a quality flag of 1 (reliable redshifts), −1 (reliable redshifts but with larger uncertainties) or −2 (unreliable redshifts). Over half (60 per cent) of the measured redshifts are of high quality (\(\geq -1\)). Some of the objects however, have an unreliable redshift (10 per cent), or in some cases no redshift could be determined (30 per cent). A table containing all the measured redshifts (and EW[O\textsc{ii}]) is available in the electronic version of the paper (see Table C1 for a shorter version).

\(^2\) For description and download of the pipeline visit: http://www.ing.iac.es/Astronomy/instruments/af2/pipeline.html
In total, we measured 512 new reliable (quality flag $\geq -1$) redshifts in A2192 and A963. The redshift distributions for the surveyed volumes are shown in the top panels of Fig. 5. Note that the redshift distribution of the H$_{\text{i}}$-detected galaxies is overplotted in the histograms for reference, although the complete analysis of the distribution and properties of the H$_{\text{i}}$-detected galaxies will be presented in subsequent papers. We refer to Jaffé et al. (2012) for first results on the H$_{\text{i}}$ distribution in A2192’s main cluster.

We estimate the typical redshift error from galaxies that have been observed more than once (i.e. in more than one configuration) and we get an uncertainty of $\pm 0.0003$. We further cross-checked our redshift measurements with previous spectroscopic observations, available for a substantial number of galaxies in our sample and confirmed the quality of our redshift measurements.

In addition to the redshifts, we also measured rest-frame equivalent widths (EW) of the [O \text{II}] 3727 Å line, which will be used...
as a proxy for ongoing star formation in forthcoming papers. The EW[O\text{II}] values are listed in Table C1 for future reference.

### 3.4 Completeness and success rate

For our analysis in this and other forthcoming papers, it is very important to know the spectroscopic completeness, as it will affect local densities, or any magnitude-dependent analysis (e.g. the different galaxy population fractions inside clusters).

First, we assessed the completeness as a function of magnitude ($m$) as follows:

$$C(m) = \frac{N_c}{N_{\text{tot}}(m)},$$

where $N_c$ is the number of galaxies with reliable redshift (quality flag $\geq -1$) and $N_{\text{tot}}$ is the total number of targeted galaxies for spectroscopy (i.e. all the galaxies in our photometry that lie inside the CMD box and are inside the unvignetted field of view of the WHT, cf. Section 3).

The success rate, i.e. the fraction of galaxies with trusted redshift determination with respect to the total number of galaxies observed, is defined as:

$$SR(m) = \frac{N_c}{N_{\text{obs}}(m)},$$

where $N_{\text{obs}}$ is the number of galaxies spectroscopically observed.

This assessment of the completeness only gives a general idea of our completeness limits, as shown in Fig. 6. In the upper panel, the magnitude distribution of the targeted, observed and reliable-redshift samples are shown, and in the lower panels the completeness and success rate as a function of magnitude are plotted. This plot shows that our sample is complete to >40 per cent almost across all magnitudes.

To accurately correct for completeness, we further quantified possible changes with colour and spatial distribution. We did this by computing the completeness in colour–magnitude bins and in $\alpha-\delta$ bins. Colour bins were $\sim0.5$ mag wide, and geometrical bins were $\sim0.3$. The $R$-band magnitude bins were larger towards the brighter end to allow a similar number of galaxies in each colour–magnitude bin. The geometrical effects could be caused by fibre collisions in the cluster centre, where there is more crowding.

The effect is expected to be small as we had several configurations of the same cluster. Nevertheless, a geometrical completeness ($C_{\text{geo}}$) was calculated after applying the colour–magnitude completeness correction ($C_{\text{CM}}$).

The colour–magnitude and geometrical completeness functions will be applied to the spectroscopic sample in the following papers of the series to calculate fractions of a given galaxy population (e.g. the fraction of H\text{I}-detected galaxies as a function of environment). This can be achieved by weighting each galaxy by $C_{\text{CM}} + C_{\text{geo}}$, where $\Sigma(C_{\text{CM}}) = N_{\text{obs}}$ and $\Sigma(C_{\text{geo}}) = 1$.

### 4 VELOCITY DISPERSIONS AND CLUSTER/GROUP MEMBERSHIP

To identify the main clusters and other structures in the fields of A963 and A2192, we used the following approach.

Using galaxies with high-quality redshifts ($\geq -1$), we constructed redshift histograms and identified (by eye) possible galaxy overdensities. This is shown in the top panels of Fig. 5, where all the identified structures are highlighted.

Following the approach of Beers, Flynn & Gebhardt (1990), we computed the cluster velocity dispersion and central redshift in each case. Equation (3) shows the definition of the peculiar velocity of a galaxy with redshift $z$ in the rest frame of a cluster with redshift $z_{\text{cl}}$. This equation is valid to first order for $v \ll c$ (Harrison 1974; Carlberg et al. 1996). The velocity dispersion of the cluster ($\sigma_{\text{cl}}$) is then defined as the dispersion of the $v$ values for the cluster members. This value is related to the observed velocity dispersion ($\sigma_{\text{obs}}$), as shown in equation (4).

$$v = c \frac{z - z_{\text{cl}}}{1 + z_{\text{cl}}}$$

$$\sigma_{\text{cl}} = \frac{\sigma_{\text{obs}}}{1 + z_{\text{cl}}}$$

Because the velocity dispersion of a cluster is a proxy for cluster mass (see Finn et al. 2005), we use it to distinguish galaxy clusters from less massive groups. Although there is no strict velocity dispersion cutoff for separating groups from poor clusters, in our environmental definition, we adopt a threshold value of 500 km s$^{-1}$, following Mulchaey (2000).

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**Figure 6.** The top panels in this figure show the magnitude distribution of the targeted sample (solid histogram), in addition to the observed targets (blue dashed histogram) and the observed targets with trusted redshifts (red dotted histogram) for A963 (left) and A2192 (right). The middle and bottom panels show the completeness and success rate (respectively) as a function of magnitude. All the available redshifts were used to compute the completeness.
We further calculated $R_{200}$, the radius delimiting a sphere with a mean density equal to 200 times the critical density,\(^3\) as in Poggianti et al. (2006):

$$R_{200} = 1.73 \frac{\sigma_{cl}}{1000 \text{ km s}^{-1}} \left(\frac{1}{\Omega_{\Lambda} + \Omega_0 (1 + z_c)^3}\right) h^{-1} \text{ Mpc}. \quad (5)$$

To carefully distinguish between environments, we classify galaxies within or around a cluster or group in the following categories: cluster, cluster outskirts and field. For this, we make use of $R_{200}$ and the so-called turnaround radius, $R_t$, that separates the infall region and the field. Following the work of Rines & Diaferio (2006), we assume that $R_t / R_{200} = 4.57$. We define cluster galaxies to be inside $R_{200}$, outskirt galaxies to lie between $R_{200}$ and $R_t$ and field galaxies to be beyond $R_t$, as shown schematically in Fig. 7.

Table 4 lists the $\sigma_{cl}, R_{200}$, central redshift and number of members for each structure found inside the H\(_i\) survey’s volume. Table A1 lists other structures identified outside the studied redshift range.

## 5 CLUSTER SUBSTRUCTURE

Numerical dark matter simulations of galaxy groups and clusters in a $\Lambda$CDM universe predict that a significant fraction (30 per cent) of all systems should contain substructure (Knebe & Mülner 2000). Because it reflects the dynamical state of a cluster, it is thus important to quantify the incidence of substructure, and to take it into account when studying galaxy properties as a function of environment. In Jaffé et al. (2012), we showed that A2192_1 is a cluster with very clear spatially and dynamically distinct substructures inside it. Our analysis suggested that it is a cluster that is in the process of forming.

There are many ways to detect substructure in clusters. A first approach is to study the Gaussianity of the velocity distribution. For example, from Fig. 5 (middle-right panel) alone, we can note a double peak in A2192_1 that already suggests the presence of substructure. However, velocity information alone does not necessarily reveal substructures within a cluster. Instead, it is important to look for deviations in the spatial and velocity distribution of galaxies simultaneously.

### 5.1 A three-dimensional view of the clusters

To study and identify the presence of substructure within the clusters, we looked for deviations in the spatial and/or velocity distribution of galaxies in each structure. One way to do this is to visually inspect three-dimensional (3D) maps of the galaxies’ $\alpha, \delta$ and redshift space. Fig. 8 shows the 3D maps, centred on the richest structures in the survey.

From this exercise, we can clearly see galaxy overdensities that are well separated in space and velocity. The most striking case is that of A2192_1, because it shows clearly four separated substructures in space and velocity (coloured in red, grey, yellow and turquoise). This cluster has been thoroughly analysed in Jaffé et al. (2012), where we have also studied the distribution of H\(_i\)-detected galaxies around the substructures. A963_1 on the other hand presents a different case. It is populated by more galaxies than A2192_1 and their distribution in 3D space is more homogeneous.

A clear feature is the ‘finger’ of galaxies along the z direction, that represents the cluster core, but in the 3D distribution of this cluster there are no easily distinguishable substructures. In the following (Section 5.2), we will complement the 3D view of the clusters with statistical substructure tests, and in Section 6, we summarize the results of our environment analysis.

### 5.2 The Dressler–Shectman test

To further test the presence of substructure in the clusters and groups, we carried out the Dressler–Shectman (DS) test (Dressler & Shectman 1988), that compares the local velocity and velocity dispersion for each galaxy with the global values. To do this, we define $v_{cl}$ and $\sigma_{cl}$ as the mean velocity and velocity dispersion of the cluster/group, which is assumed to have $N_{mem}$ galaxies. Then, for each galaxy $i$, we select a subsample of galaxies containing the galaxy $i$, plus its nearest $N_{nn}$ neighbours, and compute their mean velocity $v_{local}$ and velocity dispersion $\sigma_{local}$. From these, we compute the individual galaxy deviations $\delta^2$, following:

$$\delta^2_i = \left(\frac{N_{nn} + 1}{\sigma_{cl}^2}\right) \left[(\bar{v}_i - \bar{v})^2 + (\sigma_{local} - \sigma_{cl})^2\right]. \quad (6)$$

We used $N_{nn} = 10$ in our clusters and $N_{nn} = \sqrt{N_{mem}}$ in groups with less than 20 members.

We performed two DS statistical tests.

(i) The first is the ‘critical value’ method, in which a $\Delta$-value is computed by

$$\Delta = \sum_i \delta^2_i. \quad (7)$$

Then, a system is considered to have substructure if $\Delta/N_{mem} > 1$.

(ii) The second method uses probabilities ($P$) rather than critical values. The $P$-values are computed by comparing the $\Delta$-value to ‘shuffled’ $\Delta$-values, which are computed by randomly shuffling the observed velocities and reassigning these values to the member positions (i.e. Monte Carlo shuffling). The $P$-values are given by

$$P = \sum_{\Delta_{\text{shuffle}} > \Delta_{\text{obs}}} N_{\text{shuffle}} / N_{\text{shuffle}}. \quad (8)$$

Where $\Delta_{\text{shuffle}}$ and $\Delta_{\text{obs}}$ are computed following equation (7) and $N_{\text{shuffle}}$ is the number of Monte Carlo shuffles performed, typically around 5000. A system is then considered to host substructure if it has a very small $P$-value ($\leq 0.01$), as it is unlikely to obtain $\Delta_{\text{obs}}$ randomly.

\(^3\) $R_{200}$ is commonly used as an equivalent of virial radius.
Figure 8. 3D visualization of the distribution of galaxies in the main clusters. The galaxies are plotted in right ascension versus declination versus redshift. The left-hand panel shows the massive cluster A963_1 (red), its substructures A963_1a and A963_1b, coloured in turquoise and green respectively (see Sections 5.2 and 6), and A963_1’s smaller nearby companion, A963_2 (blue). Smaller symbols represent the galaxies with less reliable redshifts (including the cluster members from Lavery & Henry 1994). The right-hand side shows A2192_1 split into its substructures: A2192_1a (red), A2192_1b (grey), A2192_1c (turquoise) and A2192_1d (yellow). This figure is three-dimensionally interactive in the online version of the paper, allowing the reader to change the magnification and viewing angle. The plots were constructed with the S2PLOT programming library (Barnes et al. 2006). A recent version of Adobe Acrobat Reader is required to display the content of this figure correctly. Click on each panel to activate the figure. Movies of the animated figures can also be found on the BUDHIES website http://www.astro.rug.nl/budhies/, or in the online supplementary material.

Table 3. Results from the Dressler–Schectman test for substructure. Higher values of $\frac{\Delta_{\text{obs}}}{N_{\text{mem}}}$ indicate more likeliness to host substructure. Inversely, lower values of $P$ indicate a higher probability that the cluster/group has significant substructure. We adopt $P \lesssim 0.01$ to identify the cluster/groups with significant substructure.

<table>
<thead>
<tr>
<th>Name of structure</th>
<th>$N_{\text{mem}}$</th>
<th>$\frac{\Delta_{\text{obs}}}{N_{\text{mem}}}$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A963_1</td>
<td>140</td>
<td>1.44</td>
<td>0.005</td>
</tr>
<tr>
<td>A963_2</td>
<td>21</td>
<td>1.65</td>
<td>0.27</td>
</tr>
<tr>
<td>A963_3</td>
<td>16</td>
<td>1.43</td>
<td>0.5</td>
</tr>
<tr>
<td>A2192_1</td>
<td>103</td>
<td>1.96</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>A2192_2</td>
<td>15</td>
<td>1.91</td>
<td>0.015</td>
</tr>
<tr>
<td>A2192_3</td>
<td>11</td>
<td>1.79</td>
<td>0.011</td>
</tr>
</tbody>
</table>

We applied both methods to the spectroscopic sample (see Table 3), but focus on the $P$-values to identify cluster/groups with substructure. We found that the main clusters, A2192_1 and A963_1 have very small $P$-values ($\lesssim 0.01$), which strongly suggests that they have significant substructure. The other clusters and groups have smaller, although non negligible, probabilities of hosting substructure (i.e. higher $P$-values).

Figs 10 and B1 further show the Dressler & Schectman (1988) ‘bubble plots’ for each cluster/group in our sample. In these plots, each galaxy is marked by a circle with a size proportional to $\exp(\delta_i)$, so that galaxies with kinematics deviating significantly from the kinematics of the cluster can be easily identified. In our study, we considered significant deviations those with $\exp(\delta_i) \gtrsim 6$. In these figures, the spectroscopic sample defined in Section 3.1 was utilized. Only high-quality redshifts ($\geq -1$) were considered, which excludes literature data from Lavery & Henry (1994, and private communication).

We used the ‘bubble plots’ to confirm the substructures found in Fig. 8 for A2192_1 (see also Jaffé et al. 2012) and further identify less obvious substructures in A963_1. First, we selected groups of galaxies with bigger circles in the bubble plots (i.e. significant kinematic deviation from the cluster) in a similar manner as in Bravo-Alfaro et al. (2009). In addition to this, once a substructure (i.e. a group of galaxies with similar-size circles) was identified, we examined the velocity distribution and discarded clear outliers. In this way, we can be more certain that the substructures we identify are not only spatially concentrated, but also have consistent velocities. For this reason, the substructures coloured in Fig. 9 may have similar-sized uncoloured circles near them that are not considered part of the substructure (see for example the case of A963_1b). This process confirmed the reality of the four substructures found in A2192_1, and identified two poor groups with consistent velocities in the outskirts of A963_1 (A963_1a and A963_1b, fully discussed in Section 6).

Overall, the Dressler–Schectman test revealed that the substructure in A963_1 is more sparsely distributed around the cluster outskirts (bigger – black and coloured – circles outside $R_{200}$ in the left-hand side of Fig. 9), whilst for A2192_1, the substructures found (coloured circles in the right-hand side of Fig. 9) are very distinct, as we had found already in Fig. 8 and Jaffé et al. (2012) from the 3D distribution of the galaxies.

6 SUMMARY OF THE STRUCTURES

Our environmental analysis (cf. Sections 5.2 and 5.1) yielded a wide range of environments in the two surveyed volumes. Specifically, we identified two clusters, one in each field, containing well-defined...
Figure 9. The Dressler & Shectman (1988) ‘bubble plot’ for the two main clusters in our sample. Galaxies are plotted with circles with a diameter that scales with $\exp(\delta_i)$. Colours indicate substructures identified. The dashed circles indicate the $R_{200}$ radius of the clusters. Only galaxies with good-quality redshifts inside the CMD box were considered. The crosses in the centre of A963 (left-hand panel) correspond to additional cluster members from Lavery & Henry (1994, and private communication). The ‘bubble plots’ for the other clusters/groups in our sample are shown in Appendix B.

Figure 10. Schematic view of the different environments defined in this paper. The eyes looking upwards at the bottom of each panel indicate the line of sight. As a consequence redshift increases vertically (left-hand axis). Only the redshift range of the $\text{H}_\text{I}$ observations is shown. Additionally, the axes on the right of each panel indicate the velocity difference ($\Delta \text{vel}$) between each structure and the main cluster (A963_1 in the left-hand panel and A2192_1a in the right-hand panel). The sizes of the clusters have been roughly scaled for comparison, in accordance with the 1 Mpc scale (at the main cluster’s redshift) shown at the bottom right (black solid line) of each panel.
substructure within them. Together with these clusters, we found several foreground and background cluster/groups\(^4\) in the redshift range \(0.164 \leq z \leq 0.224\), as illustrated in Fig. 10. The main properties of the structures found are listed in Table 4.

In the following, we combine all our results to summarize the main characteristics of each structure.

(i) A963\(_1\): is the richest and most massive cluster in the surveyed volumes. It contains 141 spectroscopically confirmed galaxies (with \(R < 19.5\)), it has a dynamical mass of \(1.1 \times 10^{15} \, h^{-1} M_{\odot}\) and a virial radius of \(1.55 \, h^{-1} \text{Mpc}\) (both estimated from the measured \(\sigma_{cl} = 993 \, \text{km s}^{-1}\)). A963\(_1\) has previously been studied both in X-rays and using weak lensing (Allen et al. 2003; Smith et al. 2005). The cluster has been classified as ‘relaxed’, as it shows very regular and centrally concentrated X-ray and mass morphologies (on a central cD galaxy) (see fig. 6 of Smith et al. 2005), which suggests a low level of substructure. Its total mass has been estimated to be \(3.5 \pm 0.3 \times 10^{15} \, h^{-1} M_{\odot}\) from the lensing analysis, which is lower than our \(\sigma_{cl}\)-derived measure. Moreover, its total X-ray luminosity is \(L_X = 3.4 \pm 1 \times 10^{44} \, h^{-2} \text{erg s}^{-1}\), and the X-ray estimated \(R_{200}\) is \(1.2 \pm 0.1 \, h^{-1} \text{Mpc}\), which is also smaller than the dynamical value we measure (\(1.55 \, h^{-1} \text{Mpc}\), see Table 4).

Our analysis, combined with the X-ray observations, suggests that the ‘relaxed’ part of the cluster is at its core, while the substructure dominates the outskirts.

The DS test in A963\(_1\) yielded \(\Delta / N_{\text{sim}} = 1.44\) and \(P = 0.005\) (cf. Table 3), which strongly indicates it has substructure. Fig. 9 reveals a spread population of galaxies surrounding the cluster with evident velocity and spatial offsets from the cluster (see bigger – black and coloured – circles surrounding the cluster centre), suggesting it might be a population of infalling field galaxies. Moreover, there are four substructures (coloured and labelled in the figure) that could represent accreted galaxy groups in the process of destruction. This seems plausible given that they lie within the turnaround radius \((4.57 \times R_{200})\). To verify the reality of these groups, we inspected their velocity distributions, as shown in Fig. 11.

\(^4\) As explained in Section 3.3, we separate clusters from groups using a threshold cluster velocity dispersion value of \(500 \, \text{km s}^{-1}\).

Table 4. Clusters, groups and other structures identified in the fields of A963 and A2192 inside the redshift range of the H\(_1\) observations. The columns indicate the field, structure, central redshift \((z_c)\), number of members in the reduced sample (and – for the main clusters – number of members within \(R_{200}\)), cluster velocity dispersion, \(R_{200}\) and comments.

<table>
<thead>
<tr>
<th>Field</th>
<th>Name of structure</th>
<th>(z_c)</th>
<th>No. of members ((R &lt; 19.4 \text{ mag}))</th>
<th>(\sigma_{cl}) ((\text{km s}^{-1}))</th>
<th>(R_{200}) ((h^{-1} \text{ Mpc}))</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A963</td>
<td>A963(_1)</td>
<td>0.2039</td>
<td>141 (67)</td>
<td>993\pm56</td>
<td>1.55</td>
<td>Main cluster in A963</td>
</tr>
<tr>
<td>A963(_1)</td>
<td>A963(_1)a</td>
<td>0.2089</td>
<td>7</td>
<td>–</td>
<td>–</td>
<td>Small substructure in A963(_1)</td>
</tr>
<tr>
<td>A963(_1)</td>
<td>A963(_1)b</td>
<td>0.2103</td>
<td>4</td>
<td>–</td>
<td>–</td>
<td>Small substructure in A963(_1)</td>
</tr>
<tr>
<td>A963(_2)</td>
<td>A963(_2)</td>
<td>0.2178</td>
<td>21</td>
<td>507\pm158</td>
<td>0.79</td>
<td>Intermediate-size cluster near A963(_1)</td>
</tr>
<tr>
<td>A963(_3)</td>
<td>A963(_3)</td>
<td>0.1682</td>
<td>15</td>
<td>–</td>
<td>–</td>
<td>Cosmic sheet, very narrow in (z) and spread in (\alpha - \delta)</td>
</tr>
<tr>
<td>A963 field</td>
<td></td>
<td>0.164</td>
<td>(0.164 \leq z \leq 0.224)</td>
<td>30</td>
<td>–</td>
<td>Galaxies not belonging to any cluster/group</td>
</tr>
<tr>
<td>A2192</td>
<td>A2192(_1)</td>
<td>0.1876</td>
<td>103 (39)</td>
<td>645\pm42</td>
<td>1.02</td>
<td>Main cluster in A2192 (see Jaffé et al. 2012)</td>
</tr>
<tr>
<td>A2192(_1)</td>
<td>A2192(_1)a</td>
<td>0.1859</td>
<td>50</td>
<td>530\pm56</td>
<td>0.84</td>
<td>Substructure of A2192(_1)</td>
</tr>
<tr>
<td>A2192(_1)</td>
<td>A2192(_1)b</td>
<td>0.1898</td>
<td>29</td>
<td>–</td>
<td>–</td>
<td>‘Field-like’ substructure of A2192(_1)</td>
</tr>
<tr>
<td>A2192(_1)</td>
<td>A2192(_1)c</td>
<td>0.1881</td>
<td>8</td>
<td>–</td>
<td>–</td>
<td>‘Field-like’ substructure of A2192(_1)</td>
</tr>
<tr>
<td>A2192(_1)</td>
<td>A2192(_1)d</td>
<td>0.1902</td>
<td>11</td>
<td>161\pm52</td>
<td>0.25</td>
<td>Compact group, substructure of A2192(_1)</td>
</tr>
<tr>
<td>A2192(_2)</td>
<td>A2192(_2)</td>
<td>0.1707</td>
<td>17</td>
<td>477\pm103</td>
<td>0.71</td>
<td>Loose group</td>
</tr>
<tr>
<td>A2192(_3)*</td>
<td>A2192(_3)*</td>
<td>0.2255</td>
<td>30</td>
<td>340\pm71</td>
<td>0.53</td>
<td>Galaxy group</td>
</tr>
<tr>
<td>A2192 field</td>
<td></td>
<td>0.164</td>
<td>(0.164 \leq z \leq 0.224)</td>
<td>20</td>
<td>–</td>
<td>Galaxies not belonging to any cluster/group</td>
</tr>
</tbody>
</table>

\(^*\)This group spans a redshift range that exceeds the limit of the H\(_1\) survey, and hence suffers from incompleteness.

The main properties of the structures found are listed in Table 4.

Note that only two groups, namely A963\(_1\)a and A963\(_1\)b have tight velocity distributions (at 1230 and 1548 \text{ km s}^{-1}\) from the main cluster, respectively, indicating they are likely bound groups. However, in A963\(_1\)c and A963\(_1\)d there is not a clear separation in the velocity space alone. In fact, their broad velocity distributions indicate that they are not gravitationally bond groups. We thus conclude that A963\(_1\) is a cluster with significant structure, including two poor groups at \(\geq R_{200}\), but dominated by a spread population of infalling galaxies in the cluster’s outskirts.

(ii) A963\(_2\): is a \(1.4 \times 10^{14} \, h^{-1} M_{\odot}\) \((\sigma_{cl} = 507 \, \text{km s}^{-1})\) cluster located at the same position in the sky as A963\(_1\), but at slightly higher redshift. Although it is tempting to think that A963\(_2\) is in the process of falling into A963\(_1\), it is important to note that A963\(_2\) lies outside the turnaround radius of the main cluster. In fact, A963\(_2\) has a velocity difference of \(~3450 \, \text{km s}^{-1}\) from A963\(_1\)’s centre (over three times the \(\sigma_{cl}\) of A963\(_1\)), so it is unlikely that these clusters are interacting.

The velocity distribution of this cluster resembles a Gaussian, although it also shows some hints of asymmetry. In particular, it shows a prominent and narrow velocity peak at the central velocity with a normal distribution underneath it. If this feature is real, it could be interpreted as a cosmic sheet at the peak’s redshift that contains an intermediate-size cluster. Moreover, the substructure analysis in A963\(_2\) does not give strong evidence of substructure.

(iii) A963\(_3\): this family of galaxies with a narrow velocity distribution but very spread out in space, is likely to be a cosmic sheet and not a galaxy group. There is a very low probability that A963\(_3\) contains substructure, supporting the idea that this group is just a population of field galaxies at the same redshift.

(iv) A2192\(_1\): is a forming cluster with significant substructure. This cluster has been fully explored in Jaffé et al. (2012). In short, A2192\(_1\) is composed by a \(1.63 \times 10^{14} \, h^{-1} M_{\odot}\) \((\sigma_{cl} = 530 \, \text{km s}^{-1})\) cluster, A2192\(_1\)a, which is the forming cluster itself that coincides with (weak) X-ray emission. Surrounding the cluster, we find a compact group, A2192\(_1\)d, and a scattered population of ‘field-like’ galaxies A2192\(_1\)b and A2192\(_1\)c. As explained in Jaffé et al. (2012), A2192\(_1\)b and A2192\(_1\)c are ‘field-like’ because they are spread in space and their galaxy population resembles that of the...
field. These substructures, although unlikely to be bound, are considered part of A2192_1 since they are well within the turnaround radius. Supporting our findings, the Dressler–Shectman ‘bubble plot’ (right-hand side of Fig. 9) revealed the same substructures found in Fig. 8 (see also fig. 2 of Jaffé et al. 2012).

In contrast with A963_1, A2192_1 has very weak X-ray emission. However, the existent emission coincides with a group of early-type galaxies at the core of A2192_1a. Moreover, the X-ray luminosity \( \left( L_x \approx 7 \times 10^{41} \text{ erg s}^{-1} \right) \) is consistent with the derived dynamical mass.

(v) A2192_2: with a dynamical mass of \( 9.9 \times 10^{13} \, h^{-1} \, M_\odot \) \((\sigma_{cl} = 447 \, \text{km s}^{-1})\), this galaxy group is clearly separated in velocity space from the others in the field. Although its mass is very similar to that of the low-mass cluster A963_2, A2192_2 has a \( \sigma_{cl} \) below our threshold limit, so we have classified it as a group. Moreover it is considerably spread in space and has substructure, which makes it a loose group.

(vi) A2192_3: is a \( 4.21 \times 10^{13} \, h^{-1} \, M_\odot \) \((\sigma_{cl} = 340 \, \text{km s}^{-1})\) group of galaxies with little substructure.

Table 4 lists the main characteristics of the structures described above. Other cluster/groups outside the surveyed volume, but identified by our spectroscopic campaign, are listed in Table A1 for completeness.

### 7 CONCLUSIONS

With the WSRT, BUDHIES has detected H\(_i\) in over 150 galaxies in and around 2 Abell clusters at \( z \approx 0.2 \) (Deshev et al. in preparation). As part of BUDHIES, we have also carried out spectroscopic observations of the galaxies in the two surveyed volumes with AF2+WFYFFOS on the WHT. In this paper, we provide details of the spectroscopic target selection, observations and data reduction. The observations allowed us to measure many redshifts that mapped the cosmic large-scale structure in these volumes and thus characterize the environment of the H\(_i\)-detected galaxies in the surveyed volume. We present data tables containing positions, redshifts, EW of the [O \(_i\)] emission and B- and R-band magnitudes for galaxies in the surveyed volumes.

The redshift distribution revealed several structures in each of the surveyed volume, ranging from massive clusters to small groups, cosmic sheets and voids. We further present an environment classification scheme in which we consider ‘cluster’ galaxies those within \( R_{200}\), ‘outskirts’ the region between \( R_{200}\) and the turnaround radius, and ‘field’ all the galaxies beyond the turnaround radius.

By performing detailed substructure tests, we find that both main clusters (A963_1 and A2192_1) show a high degree of substructure within their turnaround radii, suggesting they are actively accreting galaxies from smaller groups or the field population. In particular, A963_1 shows weaker evidence for group accretion, and stronger evidence for accretion of (originally) field galaxies that are well spread in space and velocity. In contrast, A2192_1 has very distinct substructures, strongly implying that the cluster is in the process of forming from the accretion of galaxy groups. The other cluster/groups in the survey have less complex substructure.

The diversity of environments found in the surveyed volumes, together with the unprecedented multiwavelength data set, makes BUDHIES an ideal laboratory to study environmental dependent processes such as strangulation, tidal and ram pressure stripping and the importance of group pre-processing in galaxy evolution.

### ACKNOWLEDGEMENTS

YLJ and BMP acknowledge financial support from ASI through contract I/099/10/0, and FONDECYT grant No. 3130476. This work was supported in part by the National Science Foundation under grant No. 1009476 to Columbia University. We are grateful for support from a Da Vinci Professorship at the Kapteyn Institute. We thank Richard Jackson and Ian Skillen for their support on the new AF2 pipeline, and Daniela Bettoni for useful discussions. YLJ is grateful to Graeme Candlish for assistance creating the 3D plots.

### REFERENCES

Out of the surveyed volume, other structures identified include:

<table>
<thead>
<tr>
<th>Field</th>
<th>Name of structure</th>
<th>$z_c$</th>
<th>No. of members ($R &lt; 19.4\text{mag}$)</th>
<th>$\sigma_{cl}$ (km s$^{-1}$)</th>
<th>$R_{200}$ ($h^{-1}\text{Mpc}$)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A963</td>
<td>A963_4</td>
<td>0.1478</td>
<td>24</td>
<td>290±53</td>
<td>0.47</td>
<td>Sparse in $z$ and $\delta$</td>
</tr>
<tr>
<td></td>
<td>A963_5</td>
<td>0.1348</td>
<td>35</td>
<td>717±92</td>
<td>1.16</td>
<td>Scattered, double peaked in $z$</td>
</tr>
<tr>
<td>A2192</td>
<td>A2192_4</td>
<td>0.1581</td>
<td>26</td>
<td>454±64</td>
<td>0.73</td>
<td>Well-defined group.</td>
</tr>
<tr>
<td></td>
<td>A2192_5</td>
<td>0.1348</td>
<td>26</td>
<td>717±92</td>
<td>1.16</td>
<td>&quot;Companion&quot; of A2192_3</td>
</tr>
</tbody>
</table>

**APPENDIX A: OTHER CLUSTER/GROUPS OUTSIDE THE SURVEYED VOLUME**

In Table 4, we presented the main characteristics of the cluster/groups found in the BUDHIES volume. For completeness and future reference, we show here a list of other structures identified by our spectroscopic campaign outside the redshift range of the $H_\alpha$ survey ($0.164 \leq z \leq 0.224$).
APPENDIX B: THE DRESSLER–SHECTMAN TEST: BUBBLE PLOTS

APPENDIX C: SPECTROSCOPIC CATALOGUE

In the following, we show an example, 10 rows of the spectroscopic catalogue associated with this paper.

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Figure B1. Figure 10 showed the Dressler & Shectman (1988) 'bubble plot' for the two main clusters in our sample. We show here the remaining cluster/groups. Galaxies are plotted with circles with a diameter that scales with $\exp(\delta_i)$. The dashed circles indicate the $R_{200}$ radius of the clusters. Only galaxies with good-quality redshifts were considered.

Table C1. This table contains the optical information for the galaxies observed with the WHT for which a redshift was obtained. Only 10 example rows are shown here. The full table is available in the online version of the paper. The ID is preceded by ‘IJ’ and contains the right ascension and declination of the INT photometry in hms and dms format. The redshift quality ranges from 1 to $-2$, only redshifts $\geq -1$ are to be trusted. The type of spectra is also indicated: ‘em’ stands for emission-line spectra, ‘ab’ for absorption, ‘em+ab’ means that there are both types of features clearly visible, and ‘nan’ corresponds to galaxies with unclear spectral features.

<table>
<thead>
<tr>
<th>Field</th>
<th>ID</th>
<th>$R$  (mag)</th>
<th>$B$  (mag)</th>
<th>Redshift</th>
<th>Redshift quality</th>
<th>Type of spectra</th>
<th>EW[O II]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A963</td>
<td>IJ101527.90+390603.6</td>
<td>18.67</td>
<td>20.03</td>
<td>0.2054</td>
<td>1</td>
<td>em+ab</td>
<td>14.28</td>
</tr>
<tr>
<td>A963</td>
<td>IJ101544.32+384910.9</td>
<td>19.99</td>
<td>20.78</td>
<td>0.2064</td>
<td>1</td>
<td>em/ab</td>
<td>11.1</td>
</tr>
<tr>
<td>A963</td>
<td>IJ101532.79+384805.1</td>
<td>18.45</td>
<td>20.71</td>
<td>0.2060</td>
<td>1</td>
<td>ab</td>
<td>–</td>
</tr>
<tr>
<td>A963</td>
<td>IJ101659.58+384956.2</td>
<td>18.78</td>
<td>20.82</td>
<td>0.2066</td>
<td>$-1$</td>
<td>ab</td>
<td>–</td>
</tr>
<tr>
<td>A963</td>
<td>IJ101721.29+390602.5</td>
<td>18.47</td>
<td>20.35</td>
<td>0.1993</td>
<td>1</td>
<td>nan</td>
<td>–</td>
</tr>
<tr>
<td>A963</td>
<td>IJ101701.54+390009.3</td>
<td>19.77</td>
<td>20.85</td>
<td>0.1650</td>
<td>1</td>
<td>em</td>
<td>57.22</td>
</tr>
<tr>
<td>A963</td>
<td>IJ101534.81+390912.0</td>
<td>18.20</td>
<td>20.42</td>
<td>0.1749</td>
<td>1</td>
<td>ab</td>
<td>–</td>
</tr>
<tr>
<td>A2192</td>
<td>IJ162431.50+424621.7</td>
<td>18.29</td>
<td>19.93</td>
<td>0.2612</td>
<td>1</td>
<td>ab</td>
<td>–</td>
</tr>
<tr>
<td>A2192</td>
<td>IJ162436.20+424111.7</td>
<td>19.97</td>
<td>20.91</td>
<td>0.1427</td>
<td>$-2$</td>
<td>ab</td>
<td>–</td>
</tr>
<tr>
<td>A2192</td>
<td>IJ162658.84+421557.1</td>
<td>19.34</td>
<td>21.20</td>
<td>0.1783</td>
<td>$-1$</td>
<td>ab</td>
<td>–</td>
</tr>
</tbody>
</table>
SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Figure 9.** 3D visualization of the distribution of galaxies in the main clusters.
**Table C1.** This table contains the optical information for the galaxies observed with the WHT for which a redshift was obtained (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt250/-/DC1).

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