GMASS ultra-deep spectroscopy of galaxies at $z \sim 2^{*,**}$

V. Witnessing the assembly at $z = 1.6$ of a galaxy cluster

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ABSTRACT

Context. Clusters of galaxies represent important laboratories for studying galaxy evolution and formation. Well established and relaxed clusters are known below $z < 1.4$, as well as, clusters in formation found close to radio galaxies at $z > 2$, but the in-between redshift range, during which clusters are expected to undergo significant changes, is almost unexplored.

Aims. By studying a galaxy overdensity in redshift and angular distribution at $z = 1.6$, uncovered in the Galaxy Mass Assembly ultra-deep Spectroscopic Survey (GMASS), we provide insight into the evolution of cluster galaxies at high redshift.

Methods. We present a study of the significance of the galaxy overdensity at $z = 1.6$, Cl 0332-2742, its velocity dispersion, and X-ray emission. We identify the colour bimodality of the cluster members and compare the properties of members of Cl 0332-2742 with galaxies outside the overdensity.

Results. From the redshifts of the 42 overdensity members, we measure a velocity dispersion of 500 km s^{-1} . We conservatively estimate the overdensity in redshift space for the spike at $z = 1.6$ in the GMASS field to be 8.3 ± 1.5 . A map of the surface density of galaxies at $z = 1.6$ in the GMASS field shows that its structure is irregular with several filaments and local overdensities. The differences in the physical properties of Cl 0332-2742 member and field galaxies agree with the latest hierarchical galaxy formation models: for overdensity members, the star formation rate (*SFR*), and specific *SFR*, is approximately 50% lower than for the field galaxies; overdensity galaxies are twice the age, on average, of field galaxies; and there is a higher proportion of both massive ($M > 10^{10.7} M_{\odot}$), and early-type galaxies, inside Cl 0332-2742 than in the field. Among the 42 members, seven have spectra consistent with being passively evolving, massive galaxies. These are all located within an area where the surface density of $z = 1.6$ galaxies is highest. In a $z - J$ colour-magnitude diagram, the photometric data of these early-type galaxies are in close agreement with a theoretical red sequence of a galaxy cluster at redshift $z = 1.6$, which formed most of its stars in a short burst of star formation at $z \sim 3$.

Conclusions. We conclude that the redshift spike at $z = 1.6$ in the GMASS field represents a sheet-like structure in the cosmic web, and that the area with the highest surface density within this structure, containing already seven passively evolving galaxies, will evolve into a cluster of galaxies at a later time.

Key words. galaxies: distances and redshifts – galaxies: evolution – galaxies: formation – galaxies: clusters: general – galaxies: high-redshift

1. Introduction

Clusters of galaxies are the most massive structures in the universe. Because the evolution of structure in the early universe depends on mass, galaxy clusters play an important role in cosmology and can help to constrain cosmological parameters (e.g., [Rapetti et al. 2008](#)). Clusters are also powerful tools for studying galaxy evolution.

It is well known that environment plays an important role in galaxy evolution. Correlations between the environment of galaxies, e.g., in terms of galaxy density, and several galaxy properties, such as the age and metallicity of their stellar populations, star formation rates, and morphologies have been studied, in individual galaxy clusters and also as a function of redshift. Early observations of cluster galaxies out to $z = 0.5$ by, for example, [Butcher & Oemler \(1978, 1984\)](#) showed little evidence of evolution in the colours of the red cluster population, but detected an increase in the fraction of blue galaxies, which appeared to avoid the cluster centre. Although this *Butcher-Oemler*

* Based on observations of the VLT Large Program 173.A-0687 carried out at the European Southern Observatory, Paranal, Chile.

** Appendix A is only available at <http://www.aanda.org>

effect has been disputed, the general conclusion still stands (e.g., Ellingson et al. 2001; Tanaka et al. 2005; Andreon et al. 2006; Tran et al. 2007; Fassbender et al. 2008). Balogh et al. (2007) find that, for a given stellar mass and redshift, fewer galaxies in groups show strong [O II] emission than in field galaxies. The evolution of star formation rate appears to depend on both galaxy mass and galaxy environment (Baldry et al. 2006). The observations by Baldry et al. of a large sample of galaxies at $z < 0.1$ were compared directly with the semi-analytic models of galaxy formation by Bower et al. (2006) and Croton et al. (2006), showing closer agreement with the former. This colour-density relation has also been confirmed at higher redshifts, up to $z \sim 1.5$ (Cucciati et al. 2006; Cooper et al. 2007). At these high redshifts, few massive systems are known, as Poggianti et al. (2008) note. In addition, distant cluster surveys have studied primarily massive clusters. Poggianti et al., therefore, employ data from the ESO Distant Cluster Survey to investigate the relation between star formation activity, morphology, and local galaxy density in galaxy groups and clusters at $z = 0.4$ – 0.8 . They detect proportionally fewer galaxies with ongoing star formation in regions of higher projected density in both distant and nearby clusters, but no evidence that the star formation properties of a given Hubble type or galaxy mass depend on local environment.

A striking feature in the spectrum of an old stellar population is the 4000 Å break, above which the light of old (red) stars dominate over that of the rare young stars. This feature causes the occurrence of a sequence of red (passive) galaxies in a (suitable) colour-magnitude diagram of galaxy clusters. The tight sequence observed in both nearby and distant clusters (up to $z = 1.24$) suggests that the stars in these galaxies formed at very high redshift in a relatively short time (e.g., Stanford et al. 1998; Blakeslee et al. 2003). An analysis of stellar population properties and morphologies of red-sequence galaxies in clusters and groups from $z \sim 0.75$ to $z \sim 0.45$ by Sanchez-Blazquez et al. (2009) shows that the rate at which red-sequence galaxies evolve depends on their mass, as less massive galaxies show evidence of a more extended star formation history than more massive galaxies do. One therefore expects that, at higher redshift, the scatter in colour increases as the epoch when the stellar populations were formed is approached. Indeed, changes in the red sequence in galaxy structures have been observed between low redshift and redshifts $z = 2.2$ – 3.1 (De Lucia et al. 2007; Kodama et al. 2007; Zirm et al. 2008), in the sense that the faint end of the red sequence becomes less populated, although a dependence on cluster richness may also play a role (Andreon 2008).

Distant groups and clusters of galaxies, therefore, provide important environments for the study of galaxy evolution, especially if both passive and actively star-forming galaxy populations can be studied in detail. For the overdensities of galaxies known at high redshift, this is often problematic because their cluster members are selected on the basis of either their star formation activity (blue members, e.g., Kurk et al. 2000; Pentericci et al. 2000; Venemans et al. 2002; Steidel et al. 2005), or lack of it (red members, e.g., Best et al. 2003; Kodama et al. 2007; McCarthy et al. 2007). The most well studied high-redshift systems confirmed to be clusters on the basis of their X-ray emission, are found between $z = 1.0$ and $z = 1.4$, redshifts for which spectroscopic data of both the red and blue populations can be practically acquired (e.g., at $z = 1.26$, Demarco et al. 2007; Mei et al. 2006). These clusters were discovered either by their extended X-ray emission due to hot cluster gas (RX J0848.9+4452 at $z = 1.26$, XMMU J2235.3-2557 at $z = 1.39$, XMMXCS J2215.9-1738 at $z = 1.45$, Rosati et al. 1999; Mullis et al. 2005; Stanford et al. 2006, respectively), or by studying

near-infrared (NIR) photometry of red cluster members (ISCS J143809+341419 at $z = 1.41$ Stanford et al. 2005).

We present a galaxy overdensity at $z = 1.61$, possibly a cluster under assembly, containing both red and blue galaxy populations. In Sect. 2, we introduce the overdensity as described in other papers and describe the data set that we used to gather additional data. We also discuss the selection bias that may be present in our data. In Sect. 3, we describe the properties of the overdensity, including its velocity dispersion, an estimate of its mass, and the presence of a red sequence of galaxies. In Sect. 4, the properties of the individual galaxies in the overdensity are described, in relation also to the local density, and in comparison with galaxies in a field sample. The overdensity and its galaxies are discussed in the context of the literature in Sect. 5. In Sect. 6, the paper is summarized.

The following cosmological parameters are used throughout this paper: $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_k = 0$. Magnitudes are quoted in the AB system.

2. The data

2.1. An overdensity at $z = 1.6$

The overdensity at $z = 1.6$ was detected by means of its clustering in the redshift space of the deep spectroscopic GMASS survey (Kurk et al., in preparation). We refer to this overdensity as CI 0332-2742, which corresponds to the coordinates of the galaxy at the centre of the number density isosurfaces (see below). The GMASS survey was carried out in the field of GOODS-S, where several overdensities at various redshifts have been detected. Gilli et al. (2003) described five spikes in the X-ray source redshift distribution of this field; the second highest in terms of redshift occurs at $z = 1.62$ and contains five sources. The Poissonian probability of observing such a high number of sources, given the background count rate, is only 4×10^{-3} , which implies that this aggregation represents a significant group. Vanzella et al. (2006) also described spikes in the redshift distribution using data from the ESO/GOODS spectroscopy program of faint galaxies in the GOODS-S field. They reported that 20 galaxies have redshifts of $z \sim 1.61$ and eight other galaxies had redshift data from other surveys; all of these galaxies are distributed spatially in an apparently non-uniform way. The probability of detecting such a significant peak in redshift space by chance is less than 7×10^{-5} , according to Monte Carlo simulations of the smoothed redshift distribution of the 501 confirmed redshifts, after the second stage of the ESO/GOODS spectroscopy program.

Three old, fully-assembled, massive ($>10^{11} M_\odot$) spheroidal galaxies within the spike at $z = 1.61$ were detected in the K20 survey (Cimatti et al. 2002) and described in Cimatti et al. (2004). In another article based on GMASS results, Cimatti et al. (2008) investigated the properties of thirteen old, passive galaxies at $z > 1.4$, seven of which are at $z = 1.6$. These galaxies have stellar-mass surface-densities that are ~ 1 dex higher than local spheroids of similar mass.

An overdensity at $z = 1.6$ was also discerned in photometric redshift space by Castellano et al. (2007); these authors applied their own (2+1)D cluster finding algorithm (see also Trevese et al. 2007) to the GOODS-South Field and discovered a localized overdensity, embedded in a larger scale overdensity of galaxies at $z = 1.6$. Their method was based on an estimate of three-dimensional densities and considered simultaneously angular positions and photometric redshifts (in this case from the GOODS-MUSIC catalogue by Grazian et al. 2006).

From their analysis, several major peaks at different redshifts emerged, the peak at $z \sim 1.6$ being the most significant at $z > 1$ in the GOODS-South field. Within this large-scale overdensity (for which additional spectroscopic evidence was presented by Cimatti et al. 2002, 2004; Gilli et al. 2003; Vanzella et al. 2005, 2006), they isolated a compact, higher density peak, centred approximately on RA = $03^{\text{h}}32^{\text{m}}29.98^{\text{s}}$, Dec = $-27^{\circ}42'35.99''$, which was identified to be a cluster of an approximate total extension of 3×3 Mpc (comoving), centred on a large star-forming, remarkably irregular galaxy (see Fig. 2 in Castellano et al. 2007). In this paper, we define a circular *high-density* region, centred on the same coordinates, of radius 1 Mpc (physical). The reasons for this choice are explained in Sect. 3.1. On the basis of the irregular morphology of the galaxy overdensity, its low total X-ray emission, and its estimated mass of $(1.4\text{--}4.1) \times 10^{14} M_{\odot}$, Castellano et al. concluded that this group/poor cluster had not yet reached its virial equilibrium.

2.2. The GMASS sample

GMASS (*Galaxy Mass Assembly ultra-deep Spectroscopic Survey*¹) is a project based on an ESO VLT Large Program (173.A-0687, P.I. A. Cimatti). The GMASS project and sample are described in detail by Kurk et al. (2009, in preparation, hereafter Paper VI), and we recall only its main features. The GMASS sample was selected from a region of 6.8×6.8 arcmin², located in the GOODS-South field² (Giavalisco et al. 2004; Dickinson et al., in preparation); all sources detected in the publicly available $4.5 \mu\text{m}$ image, acquired using IRAC on the *Spitzer Space Telescope*, were extracted to a limiting magnitude of $m_{4.5} < 23.0$ ($2.3 \mu\text{Jy}$), which provided a selection related closely to stellar mass. The GMASS sample includes 1277 unblended objects to $m_{4.5} < 23.0$, which have photometry from the NUV to MIR and SED fits obtained using Maraston (2005, M05) templates providing stellar masses, star formation rates (SFRs), and other galaxy properties (see Sect. 4 and Pozzetti et al. 2007).

The GMASS ESO VLT+FOR2 optical spectroscopy was focused on galaxies pre-selected using a cut in photometric redshift of $z_{\text{phot}} > 1.4$ and two cuts in the optical magnitudes ($B < 26.5$, $I < 26.5$). This selection produced 221 spectroscopic targets, 174 of which were actually observed (called the spectroscopic sample, hereafter). The integration times were extremely long (up to 32 hours per mask and some targets were included in multiple masks), and the utility of the spectroscopic data was optimized by acquiring spectra at either blue (4000–6000 Å) or red (6000–10000 Å) wavelengths, depending on the colours and photometric SEDs of the targets, called the blue and red masks, respectively, hereafter. Despite the faintness of the targets, the GMASS spectroscopy program was very successful: we were able to determine redshifts for 150 out of the 174 targeted sources (86%), 132 of which turned out to have $z_{\text{spec}} > 1.4$. This implies that fractions of $\geq 76\%$ and 88% of all targeted sources and those with successfully determined redshifts, respectively, are at $z_{\text{spec}} > 1.4$. In addition to the 18 objects from the spectroscopic sample with $z_{\text{spec}} < 1.4$, filler objects used to complete the masks delivered another 27 redshifts of $z_{\text{spec}} < 1.4$ and three of $z_{\text{spec}} > 1.4$.

Figure 1 shows the distribution of all known spectroscopic redshifts (including those of other surveys in GOODS-S, see

Fig. 1. Redshift distribution of spectroscopic redshifts of objects in the GMASS field displayed with bin sizes of $\Delta z = 0.02$ (main panel) and 0.002 (insets). Redshifts determined within the GMASS survey are indicated by the grey histogram. Within the upper inset, the sky background relevant to [O II] detection is indicated by a dashed line. Within the lower inset, which has the same bin size but is zoomed in on a smaller redshift range, including the spike only, a curve with two Gaussian functions fitted to the histogram is overlaid. In addition, a dashed histogram showing the 21 galaxies within the high density region (see text) is included. The solid arrow indicates the redshift of the brightest member galaxy, while the dashed arrow indicates the redshift of the central (see text) galaxy.

Paper VI) of galaxies within the GMASS catalogue (stars are omitted), up to $z = 2.9$. Several peaks in the distribution are prominent, the peak at $z = 1.6$ being the most significant at $z > 1.4$. Although this peak was previously known to exist (see Sect. 2.1 for references), the availability of 136 spectroscopic redshifts at $z > 1.4$ from GMASS allows a far more careful study than possible before. The redshift peak at $z = 1.6$ may indicate the presence of a galaxy cluster or a more extended galaxy overdensity (such as a sheet). Because the dynamical state and richness of Cl 0332-2742 is a priori unknown, we refer to the galaxy aggregation as a galaxy group or cluster in formation and to the galaxies considered to be part of the spike in the redshift distribution as *members* or member galaxies.

2.3. Assessment of the spectroscopic selection bias

Our criteria for the selection of the spectroscopic sample may create a selection bias, which should have a minor influence on the redshift distribution in the range $1.4 < z < 1.8$ considered here. A bias introduced by the success of the redshift determination, could be more important. At wavelengths for which [O II] is detected, in galaxies at $z \sim 1.6$, several sky lines of a range of intensities, in the observed frame, are present. These lines can, in principle, have a serious effect on the measurement of emission-line wavelengths, and spurious peaks in the redshift distribution

¹ <http://www.arcetri.astro.it/~cimatti/gmass/gmass.html>

² <http://www.stsci.edu/science/goods>

can be produced. We find, however, that this effect has a minor influence on our redshift determination.

In Sect. 3.2, we show that the 42 galaxies in the redshift range $1.600 < z_{\text{spec}} < 1.622$ are likely to be members of the galaxy overdensity. Of these, 27 have redshifts determined only by GMASS, while ten have redshifts determined only by ESO/GOODS spectroscopy (Vanzella et al. 2006). The remaining five have redshifts determined by GMASS spectroscopy, but four of these were also observed by Vanzella et al. (two with an uncertain redshift, one of them being inconsistent with the more accurate GMASS redshift), and one was part of the K20 survey (but with an uncertain and inconsistent redshift). We examined all 42 spectra in detail and assessed whether redshift determination would have been possible without the detection of the [O II] line, which was the case for 20 (i.e., 48%) of the galaxy spectra with strong UV absorption lines. For eight of these spectra, the region about $\lambda = 9690 \text{ \AA}$, which corresponds to the wavelength of the [O II] line at $z = 1.61$, was not observed at all, while for an additional three the region was observed, but the [O II] line was not detected. A wavelength-dependent selection function is not an issue for these galaxy spectra, because the main UV absorption lines are observed in an observed-frame wavelength range for which no strong sky lines are detected.

As a second check, we assessed precisely the sky line situation about $9690 \text{ \AA}$. The result is shown in the upper inset of Fig. 1, where we have translated the wavelengths of the sky spectrum to the redshift relevant to [O II] detection. We note that the region corresponding to $1.600 < z < 1.616$ is populated by weak sky lines. In contrast, the wavelength range corresponding to $1.570 < z < 1.600$, for which not a single redshift was determined, has far lower sky line contamination. In addition, we note that in the redshift range $1.616 < z < 1.622$, corresponding to an observed wavelength range for which no sky lines are present, only one galaxy is detected.

We conclude that the observed-frame wavelength range affected by mild sky-line contamination is significantly wider than the range encompassing the overdensity redshift peak. Sky lines have, therefore, a minor influence, if any, on the measurement of redshift for the twelve members with GMASS spectroscopy, for which redshift was measured using [O II], and the ten members for which redshifts were measured by the ESO/GOODS survey.

We finally note that the redshift peak is also present in the photometric redshift distribution (see Fig. 1 in paper VI), which is subject to different selection biases and therefore unlikely to generate a peak at the same redshift by chance.

3. Overdensity properties

3.1. Angular distribution

Figure 2 shows the geometry of the GMASS field, indicating objects with known spectroscopic redshifts by small dots, galaxy members (i.e., objects with $1.600 < z_{\text{spec}} < 1.622$) by crosses or diamonds, and photometric redshifts in the range $1.43 < z_{\text{phot}} < 1.77$ by large dots. There is a distinct concentration of galaxy members towards the northern edge of the GMASS field. In addition, among the galaxy members, the red, early, and intermediate-type galaxies are most strongly concentrated towards the north. These types were determined from the spectra of the galaxies on the following basis: class 1 (early-type) have absorption lines only, class 2 (late-type) have strong emission lines, and class 1.5 (intermediate-type) have absorption lines but some emission lines (most commonly [O II]) are also present.

The brightest confirmed galaxy member (GMASS 2148 at $z = 1.609$, close to the mean redshift of the spike) is the central galaxy within a striking linear triplet of early-type galaxies, having a length of $20''$ (or 169 kpc) in the north-east of the GMASS field (see Fig. 3). The other two members of the triplet (GMASS 2196 and 2543) have redshifts $z = 1.614$ and 1.612 (respectively) and the largest difference in redshift corresponds to $\sim 575 \text{ km s}^{-1}$. The crossing time of a galaxy in this triplet is $\sim 3 \times 10^8 \text{ yr}$, indicating that these systems are possibly in the process of merging, in which case they would form one central massive galaxy with a mass of $3 \times 10^{11} M_{\odot}$. In a colour-magnitude diagram of this field, GMASS 2196 and 2543 are also located very close to GMASS 2148, the latter forming the tip of the red sequence (see Sect. 3.5). It is remarkable that this triplet of red galaxies lies about $1.5'$ (i.e., 760 kpc) eastward of the centre of the high density region and X-ray emission described by Castellano et al. (2007). This may be an indication that the cluster is not yet relaxed.

We also show in Fig. 2 the density of $z \sim 1.6$ galaxies based on photometric redshifts in the GOODS-MUSIC catalogue as filled contours (this density map is comparable to that presented by Castellano et al. 2007). This density is computed by counting the number of neighbouring galaxies at $z \sim 1.6$ within a radius (projected on the sky) of about 300 (physical) kpc (roughly the scale of galaxy groups). To normalize this number and thereby correct for edge effects and the presence of bright stars, this value is divided by the total number of galaxies in the catalogue within this radius. Contours are subsequently drawn using triangulation to obtain a regular grid. This process involves some extrapolation at the edges of the grid that produces obvious artifacts in the density maps, which should be disregarded by the reader. In Fig. 2, the redshift interval of members is taken to be $1.43 < z_{\text{phot}} < 1.77$, which is based on a comparison of photometric redshifts within the MUSIC catalogue with the redshifts of spectroscopically-confirmed members. The solid and dashed contours are based on the photometric redshifts in the GMASS catalogue, using the same redshift interval as above but including spectroscopically-confirmed galaxies within the interval and excluding galaxies with spectroscopic redshifts outside the interval. The result is a similar but not identical density map. Noteworthy is the more pronounced concentration of photometric members, which are defined to be members according to photometric redshifts, in the western part of the field, which is close to the three massive, red $z = 1.6$ galaxies confirmed by the K20 survey (Cimatti et al. 2004, just to the west of the GMASS field). The circle on this figure indicates the extent of the high-density region defined in Sect. 2.1. The radius of this circle is chosen to be 1 (physical) Mpc, similar to the size of low-redshift clusters. The area of this circular region is similar to the area of a square defined by Castellano et al. (2007) to contain the highest surface density of $z = 1.61$ galaxies. The *high-density region* contains 21 of the member galaxies; the same number is present in the area outside this region, which is five times larger and is therefore referred to as the *low-density region*.

Selection biases in the angular distribution of galaxies with spectroscopic redshifts, can be caused by bright objects preventing the detection of faint objects, for example distant galaxies, within a certain radial distance. Biases are also introduced by the design of the spectroscopic masks, which have certain geometrical constraints such as the smallest possible distance between objects included in different slits. To estimate the significance of the angular inhomogeneity displayed by the members with redshifts determined by GMASS, we carried out a counts-in-cells analysis. In each cell, we compared the total number of

Fig. 2. Density maps of galaxies at $z = 1.6$ in the GOODS-South field. Filled (solid and dashed) contours indicate the density of $1.43 < z_{\text{phot}} < 1.77$ galaxies based on the GOODS-MUSIC (GMASS) catalogue photometric (and spectroscopic) redshifts. Contours indicate $0.0, 0.25, 0.5$, and $0.75 \times$ the maximum overdensity above the median density of $z = 1.6$ galaxies. This maximum overdensity is 1.9 (4.6) times the median density. Large dots (crosses) indicate the positions of GOODS-MUSIC (GMASS) galaxies in the redshift range. Small dots indicate galaxies in the GMASS catalogue outside the redshift range. CI 0332-2742 galaxies with confirmed redshifts are indicated by additional symbols according to their morphology: circles for elliptical, squares for spiral, and triangles for irregular galaxies. The elliptical galaxies have early-type spectra, except for the two indicated with double circles, which have intermediate-type spectra. All others have late-type spectra. Diamonds indicate galaxies with redshifts confirmed by ESO GOODS spectroscopy to be in the range $1.600 < z_{\text{spec}} < 1.622$, but are not in the GMASS sample.

Fig. 3. The 20'' long triplet of $z = 1.61$ early-type galaxies (as indicated by circles). Shown are a three-colour (F606W, F775W and F850LP) image and the individual ACS bands, provided by the publicly available HST GOODS observations. The colour scaling covers the range from 0 to 25σ , and 0 to 40σ , respectively, where σ is the dispersion around the mean background level (which is zero by default here). The images are 21'' on a side. Note the much bluer foreground (and possibly background) galaxies.

objects targeted in the slits of all six GMASS masks with the number of $z = 1.6$ galaxies observed in that cell. This analysis was completed for a range of cell sizes, and showed that the angular distribution of the slits used for spectroscopy was rather homogeneous. We therefore consider any observed clustering of members on the sky as true angular clustering.

3.2. Velocity dispersion

A fundamental property of galaxy clusters, groups, and their progenitors is the velocity dispersion of their members. In virialized systems, this provides a measure of the mass contained within the system. A widely adopted estimator of cluster velocity dispersion is the biweight statistic discussed by Beers et al. (1990, hereafter BFG90). For a typical dataset of 20 to 50 galaxies, BFG90 showed that the biweight-scale estimator is a robust estimator of distribution spread and demonstrated its insensitivity to outliers. We determined the median redshift and biweight statistic of the $z = 1.6$ spike in an iterative way. We started the iterative process using all galaxies in the GMASS field with spectroscopic redshifts in the interval $1.50 < z < 1.72$. The median z_{med} for these galaxies was determined, and velocities in the cluster reference frame were computed as follows:

$$v_{\text{rest},i} = c \times \Delta z / (1 + z_{\text{med}}), \quad (1)$$

where c is the speed of light. An estimate of the velocity dispersion, σ_{spike} , of the spike was provided by the biweight statistic for all $v_{\text{rest},i}$. Subsequently, only galaxies within the velocity interval $-3\sigma_{\text{spike}} \leq v_{\text{rest},i} \leq 3\sigma_{\text{spike}}$ were included and the computation of the median redshift and velocity dispersion was repeated until no changes in the galaxies included occurred. This happened after two iterations; the 42 galaxies remaining inside the velocity interval at this stage, were defined to be members of the redshift spike. Their coordinates, GMASS IDs, and other properties are listed in Table 1.

Our measurements of cluster redshift and velocity dispersion are $z_{\text{med}} = 1.610$ and $\sigma_{\text{spike}} = 440_{-60}^{+95} \text{ km s}^{-1}$, respectively. The uncertainty in σ_{spike} was taken to be the 1σ bootstrap confidence interval estimated from 1000 Monte Carlo simulations³. Of the 42 members, 32 have secure redshifts determined by GMASS and 7 have secure redshifts determined by ESO/GOODS. The remaining three redshifts are less secure, but removing these objects from the sample does not alter our final results. Expanding the redshift interval to a width of $\pm 10\sigma_{\text{spike}}$ does not add any

members to the 42 found. In the second inset of Fig. 1, we overlay a Gaussian function that corresponds to the computed σ_{spike} . The skewness and kurtosis of the redshifts distribution are -0.23 and 3.6 , respectively. As is evident in the histogram, there is an enhancement of values, relative to a Gaussian, below the distribution mean and the distribution is much more heavy-tailed than a Gaussian (Bird & Beers 1993). A Gaussian function may not therefore be the most suitable description of the redshift distribution. This is also shown by the more robust estimators of asymmetry and tail index (Bird & Beers 1993), based on order statistics, which have values of -0.27 and 2.6 , respectively, indicating deviation from Gaussianity with significances of $>20\%$ and $>99\%$. Considering only the 21 galaxies within the high density region (dashed histogram in Fig. 1), we obtain a velocity dispersion of $\sigma_{\text{high}} = 500_{-100}^{+100} \text{ km s}^{-1}$. As this value is, within the errors, consistent with the value obtained above for the 42 members, we use the value of 500 km s^{-1} for the overdensity's velocity dispersion in the remainder of this paper.

In redshift space, the members seem to form a bimodal distribution (Fig. 1), with a main peak at $z = 1.610$ and a secondary peak at $z = 1.602$. A k-means clustering analysis indeed shows that, if the presence of two redshift groups is assumed, the most likely partitioning is into a small group of seven to ten members at a mean redshift $z = 1.603$ and a large group of the remaining members with mean redshift $z = 1.611$. We also fitted two models to the redshift distribution around $z = 1.61$, the first consisting of a single Gaussian function and the second composed of the sum of two Gaussian functions. In both cases, the area under the curve was fixed to be the area given by the histogram of the 42 member redshifts at $z = 1.6$, resulting in two and five fitting parameters, respectively. The model comprising the summed Gaussian functions, shown in Fig. 1, fits the redshift distribution more accurately: an F-test comparing these two models excludes the possibility that the 32% decrease in the value of χ^2 is solely due to chance at the 98.5% level.

The two peaks might be populated by spatially-separated groups. We applied a statistical test proposed by Dressler & Shectman (1988) to quantify possible spatial substructure using the positions of the galaxy members and their recessional velocities, but found no significant evidence that the overdensity is substructured. Pinkney et al. (1996) evaluate statistical tests for substructure in clusters of galaxies, including the Lee2D (Fitchett 1988) and Lee3D (Pinkney et al.) tests. They find that these tests are less sensitive to subclustering than the test introduced by Dressler & Shectman but have the advantage of being insensitive to non-substructure configurations that appear as substructure in other tests (such as elongation and a velocity dispersion gradient). We applied both tests to our data and found

³ The computation of σ_{spike} and its asymmetric error bars was carried out by employing the ROSTAT software package written and provided by BFG90.

Table 1. Spike galaxy redshifts, photometry, properties derived from fitted SEDs, and morphological classifications.

ID	RA and Dec	z^a	O^b	Cl ^c	4.5 μ m	z'	J	M_*^d	SFR^e	Age ^f	A_V	M^g
365	03 32 27.80 –27 48 12.0	1.609	1	2.0	23.10 ± 0.02	24.4 ± 0.1	23.9 ± 0.1	9.3 ^{+0.1} _{-0.2}	10 ⁺⁰⁶ ₋₀₃	0.26 ^{+0.25} _{-0.16}	0.3 ^{+0.2} _{-0.2}	2
648	03 32 29.81 –27 47 19.7	1.609	2	2.0	22.20 ± 0.01	23.9 ± 0.1	23.2 ± 0.1	9.7 ^{+0.1} _{-0.1}	25 ⁺⁰⁷ ₋₀₆	0.13 ^{+0.03} _{-0.03}	0.9 ^{+0.1} _{-0.1}	2
781	03 32 17.71 –27 47 02.9	1.605	3	2.0	22.54 ± 0.02	23.5 ± 0.1	23.3 ± 0.1	9.5 ^{+0.1} _{-0.1}	8 ⁺⁰¹ ₋₀₁	0.57 ^{+0.01} _{-0.06}	0.0 ^{+0.1} _{-0.0}	3
1254	03 32 20.17 –27 45 49.3	1.610	1	2.0	22.21 ± 0.02	23.6 ± 0.1	23.4 ± 0.1	9.4 ^{+0.1} _{-0.1}	34 ⁺⁰¹ ₋₀₁	0.09 ^{+0.01} _{-0.01}	0.6 ^{+0.1} _{-0.1}	1
1282	03 32 33.86 –27 45 42.6	1.621	2	2.0	21.50 ± 0.01	23.9 ± 0.1	23.1 ± 0.1	9.9 ^{+0.1} _{-0.1}	51 ⁺²⁰ ₋₁₀	0.11 ^{+0.05} _{-0.02}	1.5 ^{+0.1} _{-0.1}	2
1295	03 32 28.59 –27 45 42.2	1.611	2	2.0	23.08 ± 0.03	24.5 ± 0.1	23.7 ± 0.1	9.5 ^{+0.1} _{-0.1}	4 ⁺⁰³ ₋₀₁	0.23 ^{+0.03} _{-0.07}	0.3 ^{+0.2} _{-0.1}	3
1380	03 32 25.25 –27 45 29.0	1.612	3	2.0	22.30 ± 0.02	24.1 ± 0.1	23.4 ± 0.1	9.8 ^{+0.1} _{-0.2}	16 ⁺¹¹ ₋₀₂	0.29 ^{+0.03} _{-0.17}	0.8 ^{+0.2} _{-0.1}	3
1495	03 32 35.36 –27 45 12.6	1.611	1	2.0	21.20 ± 0.01	24.0 ± 0.1	23.3 ± 0.1	9.9 ^{+0.1} _{-0.1}	97 ⁺⁰³ ₋₀₅	0.10 ^{+0.01} _{-0.01}	1.6 ^{+0.1} _{-0.1}	3
1556	03 32 37.74 –27 45 05.5	1.607:	2	2.0	21.03 ± 0.01	24.8 ± 0.2	23.6 ± 0.1	10.4 ^{+0.1} _{-0.1}	49 ⁺¹¹ ₋₂₇	0.20 ^{+0.08} _{-0.02}	2.2 ^{+0.1} _{-0.3}	3
1667	03 32 40.99 –27 44 50.2	1.613	1	2.0	22.51 ± 0.02	25.1 ± 0.2	24.5 ± 0.1	9.4 ^{+0.1} _{-0.1}	33 ⁺⁰¹ ₋₀₅	0.09 ^{+0.02} _{-0.01}	1.8 ^{+0.1} _{-0.1}	3
1691	03 32 31.90 –27 44 45.0	1.612	1	2.0	21.11 ± 0.01	23.6 ± 0.1	22.9 ± 0.1	10.1 ^{+0.1} _{-0.1}	84 ⁺⁰⁴ ₋₁₉	0.10 ^{+0.03} _{-0.01}	1.5 ^{+0.1} _{-0.1}	3
1708	03 32 23.12 –27 44 42.2	1.607	1	2.0	20.81 ± 0.01	25.0 ± 0.2	23.8 ± 0.1	10.5 ^{+0.1} _{-0.1}	73 ⁺²⁶ ₋₃₄	0.18 ^{+0.07} _{-0.04}	2.5 ^{+0.1} _{-0.2}	3
1808	03 32 26.15 –27 44 33.3	1.609	1	2.0	22.61 ± 0.02	23.9 ± 0.1	23.5 ± 0.1	9.4 ^{+0.1} _{-0.1}	29 ⁺⁰¹ ₋₁₃	0.10 ^{+0.08} _{-0.01}	1.0 ^{+0.1} _{-0.2}	2
1871	03 32 26.82 –27 44 24.7	1.613	2	2.0	22.66 ± 0.02	23.4 ± 0.1	23.0 ± 0.1	9.5 ^{+0.1} _{-0.1}	9 ⁺⁰¹ ₋₀₁	0.40 ^{+0.01} _{-0.04}	0.0 ^{+0.1} _{-0.0}	3
1979	03 32 24.64 –27 44 07.8	1.611	1	2.0	20.95 ± 0.01	23.2 ± 0.1	22.7 ± 0.1	10.0 ^{+0.1} _{-0.1}	116 ⁺⁰⁴ ₋₀₃	0.09 ^{+0.02} _{-0.01}	1.2 ^{+0.1} _{-0.1}	3
1988	03 32 24.02 –27 44 08.3	1.610	2	2.0	22.77 ± 0.03	24.0 ± 0.1	23.6 ± 0.1	9.4 ^{+0.1} _{-0.2}	11 ⁺⁰⁷ ₋₀₂	0.29 ^{+0.12} _{-0.20}	0.4 ^{+0.2} _{-0.1}	2
2055	03 32 26.77 –27 43 58.1	1.611	1	2.0	22.21 ± 0.02	24.8 ± 0.2	23.9 ± 0.1	9.8 ^{+0.1} _{-0.1}	20 ⁺¹² ₋₀₇	0.26 ^{+0.11} _{-0.14}	1.3 ^{+0.2} _{-0.2}	2
2081	03 32 29.86 –27 43 54.8	1.601	1	2.0	22.09 ± 0.01	24.1 ± 0.1	23.4 ± 0.1	9.6 ^{+0.1} _{-0.1}	5 ⁺⁰¹ ₋₀₁	1.02 ^{+0.12} _{-0.11}	0.1 ^{+0.1} _{-0.1}	2
2111	03 32 27.94 –27 42 45.7	1.610	1	1.0	20.64 ± 0.01	24.1 ± 0.1	22.4 ± 0.1	10.6 ^{+0.1} _{-0.1}	0 ⁺⁰¹ ₋₀₀	1.14 ^{+0.06} _{-0.06}	0.0 ^{+0.1} _{-0.0}	1
2113	03 32 22.00 –27 42 43.5	1.613	1	2.0	20.37 ± 0.01	24.4 ± 0.1	23.2 ± 0.1	10.6 ^{+0.1} _{-0.1}	84 ⁺²¹ ₋₄₅	0.45 ^{+0.56} _{-0.05}	1.9 ^{+0.1} _{-0.4}	3
2142	03 32 23.54 –27 42 49.3	1.610	1	2.0	22.22 ± 0.02	24.0 ± 0.1	23.3 ± 0.1	9.8 ^{+0.1} _{-0.1}	10 ⁺⁰² ₋₀₄	0.23 ^{+0.06} _{-0.02}	0.7 ^{+0.1} _{-0.2}	2
2148	03 32 36.30 –27 42 49.5	1.609	1	1.0	19.80 ± 0.01	23.4 ± 0.1	21.8 ± 0.1	11.0 ^{+0.1} _{-0.1}	0 ⁺⁰¹ ₋₀₀	1.28 ^{+0.01} _{-0.14}	0.1 ^{+0.1} _{-0.1}	1
2180	03 32 29.56 –27 42 56.0	1.608	1	2.0	21.00 ± 0.01	23.4 ± 0.1	22.7 ± 0.1	10.2 ^{+0.1} _{-0.1}	75 ⁺²¹ ₋₀₉	0.13 ^{+0.01} _{-0.03}	1.4 ^{+0.1} _{-0.1}	2
2196	03 32 36.67 –27 42 58.5	1.614	1	1.0	20.34 ± 0.01	23.8 ± 0.1	22.2 ± 0.1	10.7 ^{+0.1} _{-0.1}	0 ⁺⁰¹ ₋₀₀	1.14 ^{+0.14} _{-0.01}	0.0 ^{+0.1} _{-0.0}	1
2251	03 32 29.48 –27 43 22.0	1.609	1	2.0	20.64 ± 0.01	23.7 ± 0.1	22.6 ± 0.1	10.5 ^{+0.1} _{-0.1}	7 ⁺⁰⁶ ₋₀₁	0.90 ^{+0.04} _{-0.15}	0.5 ^{+0.2} _{-0.1}	2
2286	03 32 29.99 –27 43 22.6	1.604	1	1.0	20.82 ± 0.01	24.3 ± 0.1	22.9 ± 0.1	10.5 ^{+0.1} _{-0.1}	0 ⁺⁰¹ ₋₀₀	1.02 ^{+0.12} _{-0.08}	0.2 ^{+0.1} _{-0.1}	1
2341	03 32 17.52 –27 43 36.6	1.602	3	2.0	22.47 ± 0.02	24.0 ± 0.1	23.4 ± 0.1	9.6 ^{+0.1} _{-0.1}	7 ⁺⁰² ₋₀₁	0.81 ^{+0.33} _{-0.35}	0.2 ^{+0.1} _{-0.1}	2
2352	03 32 33.88 –27 42 04.1	1.604	1	2.0	20.09 ± 0.01	23.4 ± 0.1	22.1 ± 0.1	10.8 ^{+0.1} _{-0.1}	22 ⁺⁰⁸ ₋₁₄	0.36 ^{+0.09} _{-0.03}	1.0 ^{+0.1} _{-0.4}	2
2355	03 32 14.32 –27 43 32.9	1.610	1	1.0	20.92 ± 0.01	24.2 ± 0.1	22.7 ± 0.1	10.4 ^{+0.1} _{-0.1}	0 ⁺⁰¹ ₋₀₀	0.90 ^{+0.01} _{-0.10}	0.0 ^{+0.1} _{-0.0}	1
2361	03 32 26.05 –27 42 36.6	1.609	3	1.5	20.40 ± 0.01	23.9 ± 0.1	22.3 ± 0.1	10.8 ^{+0.1} _{-0.1}	0 ⁺⁰¹ ₋₀₀	1.43 ^{+0.27} _{-0.01}	0.2 ^{+0.1} _{-0.1}	1
2368	03 32 17.10 –27 43 41.9	1.612	1	2.0	21.15 ± 0.01	24.0 ± 0.1	23.3 ± 0.1	10.0 ^{+0.3} _{-0.1}	108 ⁺⁰³ ₋₆₅	0.10 ^{+0.41} _{-0.01}	1.6 ^{+0.1} _{-0.4}	2
2438	03 32 26.41 –27 42 28.4	1.615	2	2.0	20.87 ± 0.01	23.5 ± 0.1	22.9 ± 0.1	10.2 ^{+0.1} _{-0.1}	83 ⁺²⁵ ₋₁₇	0.26 ^{+0.11} _{-0.15}	1.4 ^{+0.1} _{-0.1}	2
2454	03 32 28.91 –27 43 03.6	1.602	1	2.0	20.80 ± 0.01	24.0 ± 0.1	23.4 ± 0.1	10.1 ^{+0.1} _{-0.1}	153 ⁺⁰² ₋₀₄	0.09 ^{+0.01} _{-0.01}	1.8 ^{+0.1} _{-0.1}	3
2493	03 32 38.51 –27 42 28.0	1.607	1	2.0	20.88 ± 0.01	23.3 ± 0.1	22.6 ± 0.1	10.2 ^{+0.1} _{-0.1}	114 ⁺⁰³ ₋₂₅	0.10 ^{+0.03} _{-0.01}	1.4 ^{+0.1} _{-0.1}	3
2540	03 32 30.33 –27 42 40.3	1.613	1	2.0	21.40 ± 0.01	23.7 ± 0.1	22.9 ± 0.1	10.1 ^{+0.1} _{-0.1}	51 ⁺¹⁵ ₋₁₀	0.14 ^{+0.03} _{-0.03}	1.0 ^{+0.1} _{-0.1}	3
2543	03 32 35.92 –27 42 41.0	1.612	1	1.5	20.26 ± 0.01	24.6 ± 0.1	22.8 ± 0.1	10.7 ^{+0.1} _{-0.1}	0 ⁺⁰¹ ₋₀₀	1.02 ^{+0.09} _{-0.03}	0.6 ^{+0.1} _{-0.1}	1
2550	03 32 30.08 –27 42 12.2	1.601	1	2.0	22.03 ± 0.01	23.9 ± 0.1	23.3 ± 0.1	9.7 ^{+0.1} _{-0.1}	39 ⁺⁰⁴ ₋₀₈	0.09 ^{+0.05} _{-0.01}	1.0 ^{+0.1} _{-0.1}	2
2603	03 32 27.85 –27 43 05.7	1.612	1	2.0	21.74 ± 0.01	23.6 ± 0.1	23.1 ± 0.1	9.9 ^{+0.1} _{-0.1}	41 ⁺¹⁴ ₋₀₅	0.13 ^{+0.01} _{-0.04}	0.9 ^{+0.1} _{-0.1}	2
505	03 32 43.37 –27 47 43.5	1.610:	2	2.0	22.86 ± 0.02	24.5 ± 0.1	23.9 ± 0.1	9.3 ^{+0.2} _{-0.1}	15 ⁺⁰⁶ ₋₀₇	0.10 ^{+0.13} _{-0.01}	0.8 ^{+0.1} _{-0.2}	3
1081	03 32 17.51 –27 46 14.0	1.610	2	2.0	21.03 ± 0.01	23.4 ± 0.1	22.8 ± 0.1	10.0 ^{+0.1} _{-0.1}	125 ⁺⁰¹ ₋₂₂	0.09 ^{+0.02} _{-0.01}	1.5 ^{+0.1} _{-0.1}	3
1399	03 32 41.66 –27 45 25.6	1.615	1	2.0	22.71 ± 0.02	24.6 ± 0.1	24.1 ± 0.1	9.3 ^{+0.2} _{-0.1}	17 ⁺⁰⁷ ₋₀₄	0.09 ^{+0.16} _{-0.01}	1.0 ^{+0.1} _{-0.1}	3
1413	03 32 24.66 –27 45 21.6	1.614:	2	2.0	21.50 ± 0.01	23.8 ± 0.1	23.2 ± 0.1	9.8 ^{+0.1} _{-0.1}	87 ⁺⁰¹ ₋₀₁	0.09 ^{+0.01} _{-0.01}	1.2 ^{+0.1} _{-0.1}	3

^a Spectroscopic redshift, colon indicates uncertain redshift. ^b Origin of redshift: (1) GMASS (2) ESO/GOODS. ^c Spectral class: (1.0) early type, (1.5) early type with signs of star formation, (2.0) late type. ^d Logarithm of stellar mass in solar masses. ^e SFR in solar mass per year. ^f Age in Gyr. ^g Morphology: (1) Elliptical (2) Spiral (3) Irregular.

marginal evidence of substructure using the Lee2D test and no evidence using the Lee3D test. The tests infer a consistent angle for the line, on which the projected member positions show the largest contrast at $\sim 75^\circ$ wrt the line of constant declination. As this angle is almost identical to the position angle of the GMASS field plotted on Fig. 2, we do not indicate this angle separately. We note that the six masks used to acquire the GMASS spectroscopy all had different position angles and the similarity between the two angles described above is considered to be a coincidence. Finally, the two-dimensional two-sided K-S test

(Fasano & Franceschini 1987) also showed that the angular distribution of the eleven $1.600 < z \leq 1.608$ galaxies does not differ significantly from that of the 31 galaxies in the interval $1.608 < z < 1.622$. Although no clear separation in projection is evident between the two redshift groups, we cannot exclude the existence of substructure along the line of sight.

For a relaxed cluster, the virial radius is similar to R_{200} , the radius inside which the density is 200 times the critical density. Using the redshift dependence of the critical density and

the virial mass to relate the line-of-sight velocity dispersion to the cluster mass, R_{200} can be expressed as (see [Finn et al. 2005](#))

$$R_{200} = 2.47 \frac{\sigma}{1000 \text{ km s}^{-1}} \frac{1}{\sqrt{\Omega_{\Lambda} + \Omega_{\text{m}}(1+z)^3}} h_{70}^{-1} \text{ Mpc}. \quad (2)$$

In addition, the virial mass of a cluster can be expressed as a function of velocity dispersion using the above equation. Assuming that the virial radius is equal to R_{200} , one obtains (see also [Finn et al. 2005](#))

$$M_{\text{vir}} = \frac{3 \sigma R_{200}}{G}, \quad (3)$$

and

$$M_{\text{vir}} = 1.7 \times 10^{15} \left(\frac{\sigma}{1000 \text{ km s}^{-1}} \right)^3 \frac{1}{\sqrt{\Omega_{\Lambda} + \Omega_{\text{m}}(1+z)^3}} h_{70}^{-1} M_{\odot}. \quad (4)$$

Although we do not know whether the structure under study here is virialized, we do apply these equations to derive an indication of the virial radius and mass, obtaining (for $\sigma = 500 \text{ km s}^{-1}$) $R_{200} = 0.5 \text{ Mpc}$ and $M_{\text{vir}} = 9 \times 10^{13} M_{\odot}$.

3.3. Galaxy overdensity and mass contained

The galaxy overdensity in redshift space is defined to be the number of galaxies found in a certain redshift interval, divided by the number of galaxies expected in this interval minus one. To determine a galaxy overdensity in redshift space, one has to assume an expected number of galaxies in this interval. It is obviously impossible to estimate the expected number of galaxies without introducing any biases such as those discussed in Sect. 2.3. In the absence of a superior method, we assume a flat $n(z)$ distribution and employ the 108 galaxies with spectroscopically-confirmed redshifts within the GMASS sample in the range $z_1 = 1.400 < z < 1.900 = z_2$. The lower limit is set by the selection criteria for GMASS spectroscopic observations and the upper limit is based on the appearance of the redshift distribution shown in Fig. 1, which declines at $z > 2$. Indeed the number of galaxies expected varies by less than 5% for $1.75 < z_2 < 2.00$. For the redshift interval $1.601 < z < 1.621$ with $\Delta z = 0.02$, 4.32 galaxies would be expected but 40 are observed (subtracting the two galaxies that define the boundaries of this interval). Therefore, we derive an estimated overdensity of $40/4.32 - 1 = 8.3 \pm 1.5$, where the uncertainty is based on Poisson statistics. We note that restricting the redshift interval of the peak to $1.601 < z < 1.615$, i.e., excluding a single galaxy, leads to an estimated overdensity of $39/3.02 - 1 = 11.9 \pm 2.2$. In addition, excluding the redshift interval $1.572 < z < 1.670$ from the $n(z)$ count, which includes all member galaxies and additional empty redshift space, the estimated overdensity would be $40/3.28 - 1 = 11.2 \pm 2.2$. In the following, we conservatively adopt an overdensity of 8.3 ± 1.5 .

To estimate the total mass contained within the volume occupied by the spike, we need to measure this volume and the matter overdensity, which is related to the galaxy overdensity by the bias factor

$$1 + b \delta_{\text{mass}} = C(1 + \delta_{\text{gal,obs}}) \quad (5)$$

(e.g., [Steidel et al. 1998](#)). The bias factor is plausibly 1.6, as extrapolated from measurements up to $z = 1.5$ by [Marinoni et al. \(2005\)](#), which is lower than the range of 2–4 assumed by [Steidel et al. \(1998\)](#), who originally introduced the method followed below. Assuming this bias factor, the matter overdensity then

equals $\delta_{\text{mass}} = 2.45^{+0.25}_{-0.30}$. Here, we assume the observed galaxy overdensity $\delta_{\text{gal,obs}} = 8.3 \pm 1.5$, which implies a value of $0.53^{+0.04}_{-0.04}$ for the factor C and takes into account the redshift-space distortions caused by the peculiar velocities of the galaxies ([Steidel et al. 1998](#)). In the transverse direction, it is difficult to estimate the spatial extent of the structure because the GMASS field does not cover the entire overdensity. We adopt two approaches here: in the first approach, we follow [Steidel et al. \(1998\)](#) and similar work ([Venemans et al. 2007](#); [Ota et al. 2008](#)), by taking the entire field sampled, while in the second, more conservative and maybe more accurate, approach, we take the localized high density region only as defined by a 1 Mpc (physical) radius from the central galaxy. In the first case, from the observed redshift depth of the overdensity of $\delta z = 0.016$, excluding the single galaxy at $z = 1.621$, and taking into account that $V_{\text{true}} = V_{\text{obs}}/C$, the mass enclosed in this volume is $\bar{\rho}_{\text{m}} V(1 + \delta_{\text{m}}) = 5.9 \pm 0.9 \times 10^{14} M_{\odot}$. The volume considered here, which is equivalent to a sphere of a $\sim 10 \text{ Mpc}$ comoving radius, is large, corresponding to a physical size of $\sim 3.8 \text{ Mpc}$ at $z = 1.61$. In the second case, the physical volume of a sphere has a physical radius of 1 Mpc, but the overdensity is almost six times larger. The mass contained in this smaller volume is therefore a fraction 0.018×6 of that stated above, or $6.4 \pm 1.0 \times 10^{13} M_{\odot}$.

The total stellar mass contained within the 21 galaxies inside the high-density region equals $\sim 6 \times 10^{11} M_{\odot}$ (the 21 galaxies inside the low density region add only another $\sim 2 \times 10^{11} M_{\odot}$). Applying a total-to-stellar-mass ratio of 100, appropriate for clusters with a velocity dispersion in the range $425\text{--}800 \text{ km s}^{-1}$ ([Balogh et al. 2007](#)), in a similar way to the approach of [McCarthy et al. \(2007\)](#) for a structure at $z = 1.5$, we obtain a total mass of $\sim 6 \times 10^{13} M_{\odot}$, which is consistent with the mass obtained above for the sphere circumscribing the high-density region.

3.4. X-ray emission

[Castellano et al. \(2007\)](#) reported three X-ray sources within the high-density region, one coinciding with the peak of their galaxy density contours and including a late-type galaxy of a peculiar morphology. We identify this galaxy with GMASS 2540, which indeed has a redshift $z = 1.613$, measured using GMASS spectroscopy. In addition, several other galaxies with spectroscopic redshifts at $z = 1.6$ from GMASS are located within the soft X-ray contours displayed in Fig. 2 of [Castellano et al.](#), namely GMASS 2180, 2286, and 2251 at $z = 1.608$, 1.604, and 1.609, respectively.

The CDFS was observed by *Chandra* for 1 Msec ([Rosati et al. 2002b](#)), which allows detection of extended emission down to $1 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.5–2 keV band for relatively compact sources. More recently, these observations were extended to 2 Msec ([Luo et al. 2008](#)). In the GMASS region, the *Chandra* PSF *FWHM* is 2–3 arcsec and the median effective exposure time at the positions of the overdensity members is 1.56 Msec. For sources with an extent of 5–10 arcsec, which are easily resolved by *Chandra*, the 2 Msec data have a detection limit ($S/N \approx 3$) of $6 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the soft band. Given the size of the GMASS field and the cumulative X-ray cluster number counts presented in [Rosati et al. \(2002a\)](#), at least ~ 4 low X-ray luminosity clusters (at any redshift) are expected to be detected. The presence of a galaxy group or cluster in this field is therefore quite likely.

At $z = 1.6$, this X-ray sensitivity implies a limit to the X-ray luminosity of $1 \times 10^{42} \text{ erg s}^{-1}$ in the observed frame and

0.5–2 keV band. For a $T = 2$ keV group, the K-correction amounts to 9 and the bolometric correction to 2.3. Therefore, the Chandra observations imply a limit of $L_{X,\text{bol}} = 2.1 \times 10^{43} \text{ erg s}^{-1}$. Mahdavi & Geller (2001) provide an empirical relation $L_X = 5 \times 10^{42} \text{ erg s}^{-1} (\sigma/330)^{4.4}$, which has significant scatter, in particular for groups. For the measured velocity dispersion of the redshift spike of $500 \pm 100 \text{ km s}^{-1}$, one would expect an X-ray luminosity $3_{-2}^{+3} \times 10^{43} \text{ erg s}^{-1}$; this is consistent with our limit because of both the large scatter in the $L_X - \sigma$ relation, and the error in the velocity dispersion, which may have been overestimated if the overdensity is not yet virialized. An extended X-ray source is detected neither in the vicinity of any ETG in the north of the field, nor around the triplet clump. In addition, by stacking X-ray photons in the 0.5–2 keV band around the seven ETGs, for a total effective exposure time of 11.3 Ms, no signal is detected down to $0.7 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$.

3.5. Colour–magnitude diagram

Although more pronounced in galaxy clusters, the field population of galaxies up to at least $z \sim 1$ shows a bimodal distribution in colour, with red galaxies on the passive side and blue galaxies on the active side, separated by a green valley of galaxies in transition from blue to red (e.g., Bell et al. 2004). The emergence of colour bimodality at $z \sim 2$ is the subject of another paper employing the GMASS spectra (Cassata et al. 2008). Within cluster populations, the bimodality is detected as a concentration of red (early-type) galaxies on a line in a colour–magnitude diagram using colours that straddle the 4000 Å break, which is referred to as the red sequence (RS). This sequence is more pronounced in regions of high galaxy density (i.e., clusters and groups) because galaxies appear to evolve more rapidly in such an environment; Thomas et al. (2005), for example, found that most of the star-formation activity in early-type galaxies probably occurred at $3 < z < 5$ in high, and at $1 < z < 2$ in low density environments. The RS was found to be present in a cluster at $z = 0.83$ (Tran et al. 2007), has been used to find clusters up to $z \sim 1.4$ (Gladders & Yee 2000), and there is evidence that the bright end ($M_* > 10^{11} M_\odot$) of the RS is populated up to $z \sim 2$ in massive cluster progenitors (Kodama et al. 2007).

For $z = 1.6$, the 4000 Å break is shifted to 10 400 Å, between the z and J bands. We plot a $z-J$ versus J diagram in Fig. 4, indicating the member galaxies by large symbols (defined according to spectral class: circles for early types, diamonds for late types, and both for intermediate types). Also indicated, by small circles, are objects without a spectroscopic redshift but with a photometric redshift in the range $1.50 < z_{\text{phot}} < 1.70$. There appear to be two populations of spectroscopic members: a blue population around $z - J = 0.6$, and a red population with $z - J \sim 1.5$. Clearly the early and intermediate types (derived from the spectra) have the reddest $z - J$ colours: all are at $z - J > 1.3$. The figure shows that, although there are many member candidates present at $z - J > 1.3$, there is also some contamination from objects (as indicated by the crosses) with spectroscopic redshifts outside the range $1.600 < z_{\text{spec}} < 1.622$.

4. Photometric, morphological, and spectral galaxy properties in spike and field

In this section, we compare the galaxy properties of member and field galaxies. The properties include the galaxy morphology, spectral type, fitted SED, and several properties derived from this SED. We refer to Cassata et al. (2008) and

Fig. 4. Colour–magnitude diagram of all objects in the GMASS catalogue (excluding those undetected in one of the two bands) showing $z-J$ colour vs. J magnitude. Large symbols indicate galaxies at $1.600 < z_{\text{spec}} < 1.622$, small circles indicate galaxies at $1.50 < z_{\text{phot}} < 1.70$ (not including those with $z_{\text{spec}} < 1.600$ or $z_{\text{spec}} > 1.622$). Galaxies with spectroscopic redshifts outside the range $1.600 < z_{\text{spec}} < 1.622$ are indicated by crosses. Spectroscopic early types are indicated by circles (5), intermediate types by both circles and boxes (2), and late types by boxes only (35). The solid (red) line indicates a theoretical red sequence observed at $z = 1.60$ for elliptical galaxies with a range of masses (as indicated in logarithmic solar masses) formed at $z_f = 3.0$. At the bottom of the plot, typical errors in colour are indicated for each J magnitude. In addition, the objects to the right of the diagonal dashed line have data of signal-to-noise ratios below three. To the right, a histogram is displayed for all member galaxies (open histogram) and for members within the range $21.5 < J < 23.0$ (indicated by dashed vertical lines in the colour–magnitude diagram) where the confirmed red-sequence galaxies are located (filled histogram).

Cimatti et al. (2008) for more details of the morphological analysis and SED fitting.

4.1. Morphological analysis

The morphological analysis was performed independently by two of us (PC and GR) in the ACS *F850LP*-band image (Cassata et al. 2008). Three classes were recognized by eye: (1) elliptical; (2) spiral; and (3) irregular. For the faint galaxies (close to $z = 1.6$), the two classifiers agreed in more than 70% of the cases. The discrepancies mainly occur for galaxies close to the boundary between spirals and irregulars, whereas agreement was obtained for 90% of the early-types. The final catalogue has been produced by a reconciliation process between the two classifiers for the remaining 30% of objects. We also determined morphological parameters by fitting the galaxy light profiles (for details of the fitting process, see Cassata et al.). We compared the classification by eye with the machine-determined parameters, obtaining the following results: 90% of the early-type galaxies (12/13) have a Sérsic index > 2 , while 88% of late-types (63/72) have a Sérsic index < 2 .

The morphological classification was carried out using the ACS *F850LP*-band image, i.e., using the rest-frame UV light of galaxies at $z = 1.6$. Therefore, surface brightness dimming and morphological k -correction may be affecting the morphological classification. On the one hand, ellipticals are expected to remain symmetrical in the UV, but fainter because of the k -correction effect. On the other hand, spirals can appear morphologically later because knots of star formation brighten in the UV and disks become fainter because of the surface brightness dimming. The combination of these two effects should not affect our visual classification, at least in separating early- and late-types. As the galaxies in our samples are observed in almost the same rest-frame UV light (the central rest-frame wavelength differs from 394 to 338 nm for redshifts between $z = 1.4$ and $z = 1.8$, respectively, while the filter has a width of 47 nm in the rest-frame), these phenomena do not introduce a differential effect on the classification of galaxies at $z = 1.4$ to $z = 1.8$.

4.2. SED fits

The properties of the stellar populations in each galaxy are determined from the SED fitting analysis for the spectroscopic redshift determined. The results of the SED fitting are, therefore, far more secure than for one where the redshift is unknown and therefore a free parameter in the fitting process, as is the case for the determination of photometric redshifts. We adopt the libraries of synthetic spectra by Maraston (2005, M05), who employs the Kroupa (2001) initial mass function (IMF) and includes the thermally pulsing asymptotic giant branch (TP-AGB) phase of stellar evolution. This phase is the dominant source of bolometric and near-IR radiation for a simple stellar population in the age range from 0.2 to 2 Gyr.

We adopt exponentially declining star-formation histories, i.e., $SFR = (M/\tau)\exp(-t/\tau)$ with $\tau = 0.1, 0.3, 1, 2, 3, 5, 10, 15$, and 30 Gyr, and, in addition, the case of a constant star-formation rate. Extinction is treated as a free parameter in the optimization, by adopting the extinction curve of Calzetti et al. (2000). We assumed solar metallicity for all the models. The fitting procedure selects the template spectrum that minimizes the χ^2 , and therefore provides a value for each of stellar population properties: the age of the best-fit model, the e -folding time of the SFR τ , the extinction A_V , and the stellar mass. In addition, the instantaneous SFR is computed from the age and τ . During the fitting, only the observed bands corresponding up to the rest-frame K_s -band ($\lambda_{\text{rest}} < 2.5 \mu\text{m}$) were used to avoid any dust-emission contamination. While the details of the procedure and its uncertainties are extensively discussed in Pozzetti et al. (2007), we recall a few points here. The median formal statistical uncertainties, derived from the width of the probability distributions in the fitting procedure, for each stellar population parameter (mass, age, SFR , A_V , τ) are approximately 10–20%. Using extensive Monte Carlo simulations, Pozzetti et al. (2007) demonstrated that the overall internal accuracy of the measured stellar masses is ~ 0.2 dex. In addition to this typical internal error, systematic errors should also be mentioned. One source of systematic error is the addition of secondary bursts to a continuous star formation history, which produces systematically higher (up to 40% on average) stellar masses. In addition, we note that the synthetic spectra including the TP-AGB phase (Maraston 2005; Charlot & Bruzual, in prep.) produce, instead, a shift of ~ 0.1 dex towards lower stellar masses than models without this important phase (Bruzual & Charlot 2003), at least for our sample. Finally, the uncertainty in the absolute value of the stellar mass, owing to assumptions

about the IMF, is within a factor of two for the IMFs typically adopted in the literature.

The galaxies with $\log(sSFR) = -7.9$ are affected by the limit set to be the minimum age of 9×10^7 yr. Since an exponential star formation history is assumed, the $sSFR$ estimate is related to the age in the following way: $sSFR \propto \exp(-t/\tau)$.

There are no strong correlations between the derived properties, apart from the following classical ones: (1) the age-metallicity correlation; and (2) the age-reddening correlation for red galaxies. The first relation is not applicable here because we do not derive the metallicity (it is fixed to be solar). The second one may be a concern as it can cause a degeneracy between dust-free galaxies with old stellar populations and dusty galaxies with young populations. However, SED fitting is able to break this degeneracy if sufficient bands are included around the (redshifted) 4000 Å break (see for example Pozzetti & Mannucci 2000, for EROs, using the RJK bands). In the case of $z = 1.6$ galaxies, the 4000 Å break is shifted to $1 \mu\text{m}$. As our SED fitting of galaxies at $z = 1.6$ includes bands up to $6.5 \mu\text{m}$, this degeneracy should not be a major concern.

4.3. Comparison of field and overdensity samples

To compare the properties of the member galaxies with those of field galaxies, we selected a sample of 43 galaxies outside the peak, that is 24 in the redshift interval $1.416 < z < 1.598$ and 19 in the interval $1.624 < z < 1.840$, which we refer to as the field sample. The field galaxies were selected from the GMASS sample and have therefore similar information available, derived in an identical way, to that for the spike galaxies. Of the 43 field galaxies, 25 have redshifts determined by GMASS only, and 8 have uncertain redshifts. We further subdivide the 42 galaxies within the redshift peak into those within the (spatially) high-density region defined in Sect. 1 (21 galaxies), and those outside (also 21, low-density region).

For an unbiased comparison of derived galaxy properties, it is necessary to know whether there are any selection effects related to the galaxy redshifts. The mass limit is mainly defined by the $m_{4.5 \mu\text{m}} < 23.0$ limit, which sets a completeness limit of about $M_* = 3 \times 10^9 M_\odot$ at $z < 1.8$ (for the M05 templates used). There are six galaxies with masses below this limit within and six outside the redshift spike. We set the fitted mass of these galaxies to $\log(M_*) = 9.5 M_\odot$ when we compare the sample masses. All SFR s below $\log(M_\odot \text{ yr}^{-1}) = -0.25$ are set to this lower limit because they are not detected in the U' band and SFR s below this value can therefore not be measured accurately. A lower limit to the age (of 9×10^7 yr) has been set by the fitting program. This enforces an upper limit to the $sSFR$ because the stellar mass is computed by assuming an exponential star formation history over the lifetime of the galaxy. In Sect. 2.3, we demonstrated that the [O II] detectability is not responsible for the high density of spectroscopically confirmed galaxies at $z = 1.6$. The contribution of [O II] detected galaxies to the sample at $z > 1.6$ is nevertheless much smaller, which might cause a bias in the sense that fewer galaxies with high star-formation rate are selected. However, the upper-left plot in Fig. 5 indicates that this is not the case. In contrast, the average SFR (derived from SED fitting) of spectroscopically confirmed $z > 1.6$ galaxies is higher than in the spike. We do not expect a redshift bias to be present for any of the other properties measured.

We compare the following properties: stellar mass, star formation rate (SFR), specific SFR ($sSFR$), i.e., SFR/mass , age, rest

Fig. 5. Comparison of galaxy properties for the galaxies in the redshift range $1.4 < z < 1.8$. From left to right and top to bottom: *SFR*, mass, *sSFR*, and age. Symbols are for galaxies within the high density region (filled circles), low density region (open circles), and outside the peak (boxes). Spectroscopic early-type galaxies are indicated by stars. The dashed lines in the fourth panel indicates the age of a galaxy formed with a short burst of star formation at $z = 2.0$ and at $z = 2.8$.

frame $B - I$ colour, spectroscopic galaxy class, and morphological class (see Table 1).

The spectroscopic class is determined by the presence of absorption lines only (1.0), emission lines only (2.0), or absorption lines with some emission lines present (1.5), in the GMASS and ESO/GOODS spectra. This classification corresponds roughly to passive, early-type (1.0), actively star-forming, late-type (2.0), and intermediate-type (1.5) galaxies. We note that the spectral type correlates well with the observed morphology, that is early-types have compact bulge-like morphologies, while late-types often show evidence for disk-like or irregular morphologies (see Figs. A.1 to A.4). There is also very good agreement between the properties derived from the SED fitting and the spectra. Cimatti et al. (2008) show that the galaxies in a sample of high-redshift (supposedly) early-type galaxies from GMASS are

red, have spheroidal morphologies and spectra consistent with a population of old, nearly passively evolving, stars. In addition, the photometric SED fitting of these galaxies gives consistent results.

Some properties of the spike and field samples are shown in Fig. 5, while the results of $K-S$ tests, which determine the probability that the properties of the various samples are drawn from the same distribution, are listed in Table 3. The values in this table are probabilities, that is a lower number indicates a more significant difference in values for the various samples. The samples compared are high versus low density, high density versus field, low density versus field, and spike versus field, respectively. The mean and the error in the mean of these properties are listed for each sample in Table 2.

Table 2. Mean and error in the mean of galaxy properties.

Prop	Unit	High	Low	Spike	Field
Mean (Standard deviation)					
Mass	$\log M_{\odot}$	10.2 (0.3)	9.8 (0.2)	10.0 (0.2)	10.0 (0.2)
SFR	$\log M_{\odot} \text{ yr}^{-1}$	1.0 (0.2)	1.4 (0.1)	1.2 (0.1)	1.5 (0.1)
$sSFR$	$\log \text{ yr}^{-1}$	-9.2 (0.2)	-8.4 (0.1)	-8.8 (0.2)	-8.5 (0.1)
Age	10^9 yr	0.6 (0.1)	0.2 (0.1)	0.4 (0.1)	0.3 (0.1)
$B - I$		0.9 (0.1)	0.7 (0.1)	0.8 (0.1)	0.8 (0.1)

Table 3. Results of the K-S tests comparing galaxy properties.

Samples ^a	High-Low	High-Field	Low-Field	S-Field
Prop	$K - S$	$K - S$	$K - S$	$K - S$
Mass	0.029	0.092	0.462	0.843
SFR	0.304	0.098	0.932	0.506
$sSFR$	0.004	0.010	0.936	0.204
Age	0.029	0.018	0.688	0.473
$B - I$	0.071	0.462	0.418	0.871
Class	0.583	0.023	0.106	0.741
Morph	0.071	0.011	0.523	0.923

^a High and low density region, in spike (S) and field (F).

There are differences for all properties listed between the high-density sample and the low-density or field sample, although some are only marginally significant. We indicate the probabilities of below 3% in boldface in Table 3. In particular, the differences in $sSFR$ and morphology are significant. These are probably driven by the presence of passively evolving galaxies with early-type morphology in the high-density region, which are not present in the low-density region.

The mean differences between the high-density region and the field amount to 0.2, 0.5, and 0.7 dex in mass, SFR , and $sSFR$, respectively, and 0.3 Gyr in age. Although there are several galaxies with masses $M > 10^{10.5} M_{\odot}$ in the field sample, there are twice as many galaxies with $M > 10^{10.7} M_{\odot}$ in the high-density sample as in the field sample, which is twice as large (six against three). The massive member galaxies are also those determined from their spectra to be early types and have the lowest $sSFR$ s. Within the spike, there are seven galaxies of early and intermediate spectral class, while outside there is only one such galaxy. We note that the more massive galaxies have higher ages.

There is a notable difference in the angular distribution of morphologically-classified elliptical galaxies in the spike: of the eight elliptical galaxies, six are inside the high-density region (see also Fig. 2). Figure 6 shows a comparison between the three samples of the morphologies and spectral classes of the galaxies.

We also studied the correlation between the $z - J$ colour, spectroscopic class, and morphology and the smaller-scale galaxy density, as computed for and shown in Fig. 2, for each galaxy. However, we did not find convincing evidence of any significant correlations.

Another interesting comparison is listed in Table 4, where values below 0.001 are printed in boldface. We display the probabilities that the following samples have properties derived from the same distribution: blue-member versus red-member galaxies, blue-member versus blue-field galaxies, red-member versus red-field galaxies, and blue-field versus red field galaxies, respectively. As expected, there are significant differences between most properties (mass, $sSFR$, age, and morphology) of the blue and red members. The properties of blue galaxies inside and outside the spike do not differ significantly, but the red members inside the spike do have lower SFR s and $sSFR$ s than the

Fig. 6. A comparison of the galaxy morphologies and spectral classes between the three samples (high and low density region, and field).**Table 4.** Blue and red galaxy property comparison.

Samples ^a	BS-RS	BS-BF	RS-RF	BF-RF
Prop	$K - S$	$K - S$	$K - S$	$K - S$
Mass	<0.0001	0.818	0.525	0.0003
SFR	0.0031	0.830	0.142	0.127
$sSFR$	<0.0001	0.592	0.103	0.451
Age	0.0002	0.741	0.051	0.598
Class	0.0124	0.983	0.103	0.122
Morph	0.0006	0.980	0.421	0.200

^a Blue (B) and red (R) galaxies, in spike (S) and field (F).

red field galaxies (the mean $sSFR$ having an order of magnitude difference). In the field, only the differences in mass and spectroscopic class are significant between the blue and red galaxies. This suggests that the red galaxies inside the overdensity have evolved more rapidly than those outside, while the blue galaxies appear to have had a similar evolution inside and outside the overdensity.

4.4. Composite spectra

Finally, in Fig. 7, we compare the rest-frame composite spectra of the 18 CI 0332-2742 galaxies that have GMASS spectra in the high-density region, with the composite spectrum of the 14 galaxies in the low-density region. Also shown in this figure are composite spectra of the 11 red and 21 blue galaxies and of the 7 early- and 25 late-type galaxies in CI 0332-2742. The composites have been normalized in the interval 2300–2700 Å, apart from the red and early-type galaxy composites, which were normalized in the interval 3000–3500 Å. It is clearly noticeable that the composite spectrum of the galaxies in the high-density region is far redder and its [O II] line equivalent width far lower (10 Å in contrast to 40 Å) than the composite spectrum of the galaxies in the low-density region. The same is true for the red and blue,

Fig. 7. Shown here are rest-frame composite spectra of several groups of Cl 0332-2742 galaxies with GMASS spectra. The *top panel* shows a comparison of the composite spectra of galaxies in the high-density region (black) and in the low-density (grey). The *middle panel* shows a comparison of red (black) and blue (grey) Cl 0332-2742 spectra, while the *bottom panel* shows the composite spectra of early- (black) and late-type (grey) galaxies in Cl 0332-2742. Absorption and emission features (possibly) identified are indicated by vertical lines below and above the spectra. In the *middle and lower panels*, the spectra are offset in vertical direction by an arbitrary amount to improve their visibility.

and early- and late-type galaxy composites ($13 \text{ \AA}$ compared to $28 \text{ \AA}$, and $2 \text{ \AA}$ compared to $36 \text{ \AA}$, respectively).

Apart from the $4000 \text{ \AA}$ and $3600 \text{ \AA}$ Balmer break (which are at $\lambda > 1 \mu\text{m}$ for $z > 1.4$ galaxies), another strong age-dependent feature in the UV is a break in the region $2640\text{--}2850 \text{ \AA}$, which is produced by the combination of several strong absorption lines, including $\text{Mg II } \lambda 2800$. Daddi et al. (2005) named this feature Mg_{UV} and defined it to be the ratio of (two times) the flux at $2625 < \lambda < 2725 \text{ \AA}$ to the flux in two $100 \text{ \AA}$ broad regions above and below this range. Daddi et al. show that only stellar populations older than 0.1 (0.4) Gyr have Mg_{UV} significantly above 1.1 (1.4). Younger stellar populations and populations with constant star formation (but reddening $E(B - V) = 1.2$) have Mg_{UV} near 1.0 . This feature is, therefore, a key signature of passively evolving stellar populations because it is not present in young dust-reddened star-forming galaxies: this therefore allows us to break the age/dust degeneracy affecting red sources. The measurement of the Mg_{UV} index for our composite spectra clearly differ: the high-density-region, red, galaxy composite has an Mg_{UV} measurement of 1.2 in contrast to 1.1 for low-density-region, blue galaxies, while the early- and late-type composites have Mg_{UV} values of 1.4 and 1.1 , respectively.

5. Discussion

We have presented evidence of a structure of galaxies at $z = 1.6$, which may be a cluster in formation. The constituent galaxies

exhibit a galaxy overdensity of at least a factor of eight and a red-sequence of passive galaxies, and they appear to be both more massive and evolved than galaxies in the field at similar redshift.

We have compared this structure with clusters at $z > 1.0$, which have similar properties, and often less reliably measured spectroscopic redshifts available. The differences in galaxy properties found by ourselves between the high density region, the low density region, and the field are consistent with the density relations found at $z \sim 1$ by Smith et al. (2005) and Postman et al. (2005), at $z = 1.24$ by Demarco et al. (2007), and at $z = 1.5$ by Fassbender et al. (2008): red early-types dominate the cluster core, while blue late-types are found in the outskirts of the cluster.

5.1. Velocity dispersion

The velocity dispersion determined for the galaxies in the high-density region and for all galaxies in Cl 0332-2742 are consistent with a value of 500 km s^{-1} . This value is about the average value that Halliday et al. (2004) and Milvang-Jensen et al. (2008) found for a sample of 26 clusters at $0.40 < z < 0.96$ selected from the ESO Distant Cluster Survey (EDisCS), but lower than the clusters at $0.8 < z < 1.3$ observed by the ACS/HST in GTO time (Postman et al. 2005), most of which were first detected by means of X-ray emission. The spike at $z = 1.6$ is therefore, as for the EDisCS clusters, more likely to be a progenitor of *typical* (less rich) low-redshift clusters (Milvang-Jensen et al. 2008).

The distribution of members of Cl 0332-2742 in redshift space is bimodal (Fig. 1), with a main peak at $z = 1.610$ and a secondary peak at $z = 1.602$. Demarco et al. (2007) found a similar bimodal redshift distribution among the 38 confirmed members of the cluster RDCS J1252.9-2927 at $z = 1.237$. In contrast to the latter cluster, we do not find evidence that the substructure in redshift space consists of two spatially separated groups, but it is probable that the bimodality of Cl 0332-2742 indicates that the structure is not yet virialized.

5.2. Red sequence

In the colour-magnitude diagram of the observed field (Fig. 4), we overplot a line that represents a theoretical red sequence at $z = 1.60$, which corresponds to the predicted magnitudes in z -band and J -band of the stellar populations of elliptical galaxies that formed in a short time (0.5 Gyr) at $z_f = 3.0$ (provided by T. Kodama, see Kodama et al. 1998, based on the code by Kodama & Arimoto 1997). We indicate the (logarithm of) stellar masses corresponding to the positions on the red sequence. The early-type galaxy members are straddled about this red sequence, with a scatter in $z - J$ of $0.147^{+0.063}_{-0.013}$ magnitude. This scatter also includes the scatter produced by photometric errors in the measured colour. Subtracting this error (averaged in quadrature over the seven galaxies) in quadrature, we obtain an intrinsic scatter of 0.135 magnitudes. The tightness in the observed red sequences at low redshift is due to the large time difference between the epoch of formation and the moment of observation. Observing red sequences at higher redshift, we approach this epoch of formation and expect the scatter to increase due to small differences in the formation time and evolution of the early-type galaxies. Stanford et al. (1998) found an intrinsic scatter of about 0.05 for clusters from $z = 0.1$ to $z = 0.8$, and Ellis et al. (2006) measured 0.2 ± 0.2 in a massive cluster at $z = 0.89$. The scatter that we measure at $z = 1.61$ is consistent with that expected from

observations at lower redshift, taking into account the younger average age of the stellar populations at this redshift.

De Lucia et al. (2007) found a clear decrease in the ratio of luminous ($L > 0.4L_*$) to faint red galaxies in clusters from $z \sim 0.8$ to $z \sim 0.4$. This increasing fraction of faint red galaxies towards lower redshift could be explained if the RS of high redshift clusters does not contain all of the progenitors of nearby RS cluster galaxies. Instead, a significant fraction of these must have moved on to the RS below $z \sim 0.8$. Although Fig. 4 appears to support this claim because of the lack of galaxies with $z_{\text{phot}} = 1.6$ on the red sequence at $J \gtrsim 23.0$, we note that, at these fainter magnitudes, we have larger errors in the photometry and photometric redshifts. We are unable to confirm this decrement in the number of faint galaxies on the RS, spectroscopically, because of the limited completeness of our spectroscopy.

The red sequence appears to be ubiquitous in the field and in clusters at low redshift, and is also detected at redshifts $z > 1$. McCarthy et al. (2007) detected one of the most distant red sequences discovered so far, at $z = 1.5$, including at least ten galaxies with very red optical-to-NIR and optical-to-MIR colours within a circle of 128 kpc radius, one of which has a spectroscopic redshift of $z = 1.51$. The total stellar mass of these galaxies is $\sim 8 \times 10^{11} M_\odot$, which is similar to the total stellar mass computed for Cl 0332-2742. Six of the galaxies lie on a red sequence in a $J - K$ CM-diagram, which is consistent with the colour-magnitude relation for the Coma cluster evolved to $z = 1.5$, assuming a passively-evolving SSP with $z_f = 5$ (according to McCarthy et al. 2007).

A bimodality in galaxy colours up to $z \sim 2$ was also found by Cassata et al. (2008) in the GMASS field and Giallongo et al. (2005) in the HDF. The latter also showed that the blue and red galaxy populations most probably had different evolutionary histories. Using a much larger sample, including $\sim 22\,000$ galaxies selected over an area of 0.6 deg^2 from the Early Data Release of the UKIDSS Ultra Deep Survey, Cirasuolo et al. (2007) found that the colour bimodality disappears at $z \gtrsim 1.5$. With a large K -selected sample of more than 30 000 galaxies, Williams et al. (2009) showed, that the bimodal distribution of star-forming and quiescent galaxies is still seen in a subsample of galaxies in the redshift range $1.5 < z < 2$, but not above $z = 2$. The clear bimodality demonstrated for Cl 0332-2742 may indicate that the colour bimodality develops earlier in high-density regions than in a field sample, such as that employed by Cirasuolo et al. and Williams et al.

The relationship between galaxy colour and environment is studied in more detail by Cooper et al. (2007, CNC07) employing a sample of 19 464 galaxies selected from the DEEP2 Galaxy Redshift Survey. They measured the galaxy surface overdensity within redshifts bins up to $z \sim 1.4$ by calculating the distance to the third closest neighbour, and the red fraction by considering $(U - B)$ -restframe colour, which is slightly dependent on luminosity. The overdensities sampled range up to about ten, which, as CNC07 state, does not cover the regime of massive clusters. CNC07 stated that the red fraction at $z > 1.4$ is not higher in high-density regions than in low-density regions, but this conclusion is based mainly on the value of a single density bin, for overdensities from 1.8 to 10. The large size of this bin may mask the higher fraction of red galaxies in the upper part of the bin. Although, because of our much smaller galaxy sample, it is difficult for us to measure the overdensity in exactly the same way as CNC07, we obtain a mean overdensity of >8 for the galaxies in Cl 0332-2742. The evidence of a red sequence in Cl 0332-2742 seems therefore at variance with the conclusion by CNC07, but the degree of inconsistency is difficult to quantify. The disagree-

ment may be explained if we are sampling a regime higher in density than studied by CNC 07.

5.3. Dependence of galaxy properties on galaxy density

We have investigated the dependence of galaxy properties on galaxy density by comparing the ensemble properties of several samples (spike, field, high, and low density) and by relating the properties of individual $z = 1.61$ galaxies to the measured local density. The latter method did not provide significant evidence of correlations between the measured galaxy properties and the local galaxy density. There may be several reasons for this lack of significant correlations. First, the local galaxy density is determined from the secure spectroscopic members and the less secure photometric members on a scale of ~ 300 (physical) kpc, which should be optimal for the detection of galaxy groups, but is rather small given the mean distance to the closest neighbour among the 42 confirmed members in the GMASS field, which is of the order of this scale. We note that, when comparing galaxy properties, only the spectroscopic members were considered, although the photometric members have a significant influence on the computation of the local galaxy density. For example, the strong density peak in the western part of the GMASS field consists almost entirely of photometric members, which certainly merit spectroscopic follow-up. It is also possible that the influence of galaxy density is notable only on larger scales, such as those of the high density region, for which we do find a significant correlation between density and all measured properties, most notably morphology.

The environmental dependence of galaxy properties was studied at higher redshift for a significant overdensity of galaxies at $z = 2.300$ by Steidel et al. (2005). They found galaxies inside the overdensity to have mean stellar masses that were higher and inferred ages that were ~ 2 times older than identically UV-selected galaxies outside the structure. This is similar to our results at $z = 1.61$. Peter et al. (2007) augmented this analysis with one of $z = 2.300$ galaxy morphologies but did not find evidence of a difference between the proto-cluster sample and a control (field) sample. Very few of the $z = 2.300$ galaxies appear to be regular ellipticals or spirals. The morphological difference between overdensity and field, which we found at $z = 1.61$, is due to the elliptical galaxies, which are also red and, using the UV selection applied at $z = 2.300$, could therefore not have been found by Steidel et al. (2005).

The lower *SFR* that Steidel et al. (2005) and ourselves found for galaxies in the overdensities compared to those in the field appears to contrast with the conclusion of Elbaz et al. (2007, EDB07) that the average *SFR* derived from FIR and UV photometry increases with galaxy density in the redshift range $0.8 \leq z \leq 1.2$. However, the range of projected galaxy densities probed by EDB07 is between 0.4 and $\sim 3 \text{ Mpc}^{-2}$ in recessional velocity bins of $v \approx 1500 \text{ km s}^{-1}$. At $z = 1.6$, this corresponds almost exactly to the redshift bin $1.600 < z < 1.623$, encompassing all 42 spike galaxies. Using this bin and the rather large boxes of $1.5 \times 1.5 \text{ Mpc}^2$ used by EDB07, the projected galaxy density in the GMASS field is 5 Mpc^{-2} on average and 10 Mpc^{-2} for the highest density regions. Obviously, using smaller boxes to count the galaxy density, as also noted by EDB07, would infer even higher projected galaxy densities (up to $\sim 40 \text{ Mpc}^{-2}$). This shows that we are probing higher densities than studied by EDB07 and their conclusions do not apply to Cl 0332-2742. Although this is probably not a statistically significant result, Figs. 8 and 9 of EDB07 appear to indicate that the *SFR* does indeed decrease at projected galaxy densities of $>3 \text{ Mpc}^{-2}$.

6. Summary and conclusions

In this section, we summarize the results presented in this paper and add a concluding remark about the galaxy structure found.

- We carried out a spectroscopic survey, called GMASS, in a region of the CDFS, targeting galaxies detected with IRAC/Spitzer at $4.5 \mu\text{m}$ and pre-selected on the basis of having a photometric redshift $z > 1.4$. We obtain spectroscopic redshifts $z > 1.4$ for 135 out of the ~ 200 observed sources (Kurk et al., in prep.).
- The redshift distribution of these sources shows a prominent peak at $z = 1.6$ consisting of 42 galaxies. We verified that the redshift distribution is not significantly affected by observational biases and find that this spike represents an overdensity in redshift space by a factor of at least eight. We call this structure Cl 0332-2742 and the galaxies at $z = 1.6$ member galaxies (of this structure).
- The angular distribution of the member galaxies is not homogeneous: within the $7' \times 7'$ GMASS field, there is a region of about 3 Mpc^2 where the number density of members is five times higher than in the rest of the field. We call this region the high density region. The brightest member is located 760 kpc away from the centre of this region, within 65 kpc of two other bright members. These galaxies are not only the brightest but also the reddest members.
- From the 42 redshifts of the members, we determine a velocity dispersion of $440^{+95}_{-60} \text{ km s}^{-1}$ for Cl 0332-2742 and of $500^{+100}_{-100} \text{ km s}^{-1}$ for the 21 members in the high density region. The redshift distribution of the 42 member galaxies is best fit by the sum of two Gaussian functions with a difference of $\delta z = 0.008$ (or 920 km s^{-1} in the reference frame of Cl 0332-2742) in their central redshifts. Although we do not find evidence of a spatial separation between the two groups of galaxies centered at $z = 1.602$ and $z = 1.610$, we cannot exclude the existence of substructure along the line of sight.
- Using various methods to derive the mass which will be or is contained within Cl 0332-2742, we find a mass within the range $6\text{--}60 \times 10^{13} M_{\odot}$. The irregularity in angular and redshift space, including at least two localized higher density peaks, suggests that the structure is not yet virialized but will evolve to become a galaxy cluster at a later cosmic time.
- We used the 1 Ms *Chandra* observations to search for hot gas associated with the high density region but did not find evidence of an X-ray luminosity $> 3.5 \times 10^{43} \text{ erg s}^{-1}$. This X-ray luminosity, however, is consistent with the expected X-ray emission for a cluster or group of galaxies with a velocity dispersion of 500 km s^{-1} .
- In a colour-magnitude diagram, a bimodal distribution of member galaxies is seen with blue galaxies around $z - J \sim 0.6$ and red galaxies, including all early-type members, at $z - J > 1.3$. The latter form a red sequence consistent with model galaxies composed of stellar populations formed at a redshift $z = 3$. The measured scatter around the red sequence of 0.135 magnitudes is consistent with the expected scatter at this redshift. The bright tip of the red sequence is formed by the triplet of bright elliptical galaxies mentioned above. We speculate that the clear bimodality seen in colour for Cl 0332-2742 members, which is stronger than in field samples at this redshift, is due to the bimodality developing earlier in volumes of high galaxy density, consistent with galaxy formation models where massive galaxies form first in the strongest density peaks present in the early universe.

- We compare various galaxy properties of the sample of member galaxies within the high density region with the sample of member galaxies outside this region and with a similarly sized *field* sample of galaxies at spectroscopic redshifts determined by GMASS in the range $1.4 < z < 1.8$, but excluding the member galaxies at $z = 1.6$. These galaxy properties include the galaxy type based on spectral features (either early or late), the galaxy morphology (either elliptical, spiral or irregular), broadband $B - I$ colour, and four properties derived from broadband SED fitting: mass, star-formation rate, specific star-formation rate, and age. The galaxies within the high density peak are on average older, more massive, and redder than those outside the redshift peak. The *SFR* and *sSFR* of the members in the high density region are on average three and five times lower than in the field. These results are consistent with current views on galaxy formation and evolution, where the most massive galaxies form preferentially in the highest density peaks of the cosmic galaxy distribution, which collapse first. The massive galaxies that we observe in the overdensity also seem to evolve more rapidly than their lower mass counterparts: they have lower specific star formation rates, already at $z = 1.6$, which implies that they have formed most of their stars by this epoch.
- We construct composite spectra of blue and red, early- and late-type members and of members in the high and low density regions. The composite spectra show features consistent with the results obtained above: the high density composite is clearly redder than the low density composite. In addition, the [O II] line equivalent width, a measure of star formation, is clearly lower in the high density composite than in the low density composite.

We note that this is the first and only structure of this kind known: its redshift of $z = 1.6$ is higher than that of any known galaxy cluster and the structure contains spectroscopically-confirmed red, early-type galaxies, whereas at higher redshifts, the known and possibly only members of galaxy overdensities are blue, star-forming galaxies are known (such as LBGs and LAEs). We therefore propose that Cl 0332-2742 may represent a link between $z < 1.4$ galaxy clusters and $z > 2$ galaxy overdensities. The extent of this structure is not limited by the size ($\sim 7' \times 7'$) of the field covered by spectroscopy carried out within the GMASS project and neither does it seem to be limited by the size of the CDFS (Castellano et al. 2007). Its extent of more than 10 Mpc therefore suggests it is a sheet in the web-like distribution of galaxies. The region with the highest surface density of galaxies within this sheet, called Cl 0332-2742 in this paper, already contains seven massive, passively evolving galaxies and already has a velocity distribution typical of a large group of galaxies in the local Universe. Since the number of passive galaxies, its velocity dispersion, and its mass can only increase during the ~ 10 Gyr between $z = 1.6$ and $z = 0$, reaching properties typical of a present-day cluster of galaxies, we conclude that, by observing Cl 0332-2742, we are witnessing the assembly of a cluster of galaxies.

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Appendix A: Spectra and images of the member galaxies

Figures [A.1–A.4](#) show the spectra and images of the member galaxies.

Fig. A.1. Spectra and postage stamp images of the 42 member galaxies. Wavelength in Angstrom on the horizontal axis and flux in $10^{-19} \text{ erg s}^{-1} \text{ \AA}^{-1} \text{ cm}^{-2}$. Uncertainties caused by background noise are indicated by the underlying filled grey spectra. As the flux calibration of the GOODS spectra is not very accurate (Vanzella et al. 2006) but the absolute flux level of these spectra seem systematically higher than the GMASS spectra (for the same magnitudes), they have been divided by a factor two. The origin of the spectra is plotted: GMASS (Kurk et al., in prep.) or GOODS (Vanzella et al. 2006), the GMASS identification numbers, and the spectroscopic classes (see text). Robust (tentative) spectral features are shown by solid (dashed) lines with numbers (see below). The postage stamps are constructed from the HST/ACS observations in the B, V, and I bands, convolved with a Gaussian kernel. Indicated are the morphological class (on the left) and the z magnitude (on the right). The spectra are sorted on $z - J$ colour, starting with the reddest galaxies. The numbers for the spectral features refer to: (1) Si II λ 1527, (2) C IV λ 1550, (3) Fe II λ 1608, (4) Al II λ 1671, (5) Al III λ 1855, (6) C III λ 1909, (7) Fe III λ 1926, (8) C II λ 2326, (9) Fe II λ 2344, (10) Fe II λ 2375, (11) Fe II λ 2383, (12) Fe II λ 2587, (13) Fe II λ 2600, (14) Mg II λ 2796, (15) Mg II λ 2804, (16) Mg I λ 2853, (17) [O II] λ 3727.

Fig. A.2. See Fig. A.1 for description.

Fig. A.3. See Fig. A.1 for description.

Fig. A.4. See Fig. A.1 for description.