A spectroscopic study of a $z = 1.6$ galaxy overdensity in the GMASS field

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Abstract. The Galaxy Mass Assembly ultra-deep Spectroscopic Survey samples a part of the CDFS to unprecedented depth. The resulting distribution of 150 $z > 1.4$ redshifts reveals a significant peak at $z = 1.6$, part of a larger overdensity found at this redshift. The 42 spectroscopic members of this structure, called Cl 0332-2742, form an overdensity in redshift of a factor 11$^{\pm}$3 and have a velocity dispersion of 450 km s$^{-1}$. We derive a total mass for Cl 0332-2742 of $\sim 7 \times 10^{14}$ M$_{\odot}$. The colours of its early-type galaxies are consistent with a theoretical red sequence of galaxies with stars formed at $z = 3.0$. In addition, there are more massive, passive and older, but less star forming galaxies in CL 0332-2742 than in the field. We conclude that this structure is a cluster under assembly at $z = 1.6$.

1. Introduction

It has been known for a considerable time that the environment plays an important role in galaxy evolution. Observations of low and high redshift clusters have provided evidence that the fraction of blue and red galaxies changes considerably between $z = 0$ and $z \sim 0.5$ (e.g., Butcher & Oemler 1984). In addition, the galaxy population inside clusters evolves at a rate different from that in the field (e.g., Andreon et al. 2006; Tran et al. 2007; Fassbender et al. 2008). Distant galaxy clusters, therefore, provide important environments for the study of galaxy evolution, especially if both passive and active galaxy populations can be studied in detail. For the known high redshift overdensities this is often problematic, because their cluster members are selected either on their star formation activity (blue members, e.g., Venemans et al. 2002; Steidel et al. 2003), or lack of it (red members, e.g., Kodama et al. 2007; McCarthy et al. 2007). The best studied, established, high redshift clusters are found between $z = 1.0$ and $z = 1.4$ (Stanford et al. 2003, 2006). We present a galaxy overdensity at $z = 1.61$, which appears to be a cluster under assembly, containing both red and blue galaxy populations.

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2. Data

GMASS (Galaxy Mass Assembly ultra-deep Spectroscopic Survey) is a project based on an ESO VLT Large Program. To obtain a mostly mass selected sample, we extracted all sources present in the 4.5 μm Spitzer/IRAC image to a limiting magnitude of $m_{4.5} < 23.0$ (2.3 μJy), in a region of 6.8 × 6.8 arcmin$^2$ located within GOODS-South. The GMASS sample includes 1277 unblended objects to $m_{4.5} < 23.0$, with photometry from the NUV to MIR and SED fits with Maraston (2005, M05) templates providing stellar masses, star formation rates and other galaxy properties. The VLT/FORS2 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 ($B, I < 26.5$). This selection resulted in 221 spectroscopic targets, 170 of which were actually observed. The integration times were very long (up to 32 hours per mask and some targets were included in multiple masks), and the spectroscopy was optimized by obtaining spectra in the blue (4000–6000 Å) or in the red (6000–10000 Å) depending on the colours and photometric redshifts of the targets. Despite the faintness of the targets, GMASS spectroscopy was very successful and provided an overall spectroscopic redshift success rate of about 85%.

Figure 1. **Left** Contours of $z = 1.6$ galaxy density as described in the text, linearly increasing up to 3.4 times the median density. Candidate members are indicated by crosses, spectroscopic members by circles (for elliptical), squares (for spiral) and triangles (for irregular galaxies). Early, late and intermediate types are indicated by white, black and white-black symbols. Diamonds indicate members not in the GMASS catalog. **Right** Colour-magnitude ($z - J$ vs $J$) diagram for the entire GMASS catalog. Galaxies with $1.600 < z_{\text{spec}} < 1.622$ are indicated by large symbols, and with $1.50 < z_{\text{phot}} < 1.70$ by small circles, except if outside $1.600 < z_{\text{spec}} < 1.622$ (crosses). The large symbols are circular for early types, and square for late types. The (red) line indicates a theoretical red sequence of elliptical galaxies, observed at $z = 1.60$, with masses indicated in logarithmic solar masses, formed at $z_f = 3.0$. Typical errors in colour are also indicated at the bottom.
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3. Results

Several peaks in the distribution of GMASS redshifts (at $z > 1.4$) stand out, the peak at $z = 1.6$ being the most significant at $z > 1.4$. Although this peak was known to exist (Gilli et al. 2003, Vanzella et al. 2005, 2006; Cimatti et al. 2002, 2004, 2008) and described in detail by Castellano et al. (2007), the availability of 136 spectroscopic redshifts at $z > 1.4$ from GMASS allows a far better study than before. We call this redshift peak Cl 0332-2742.

The angular distribution of the $z = 1.6$ galaxies in the GMASS field is shown in Fig. 1. Here we have used both spectroscopic information, showing members with $1.600 < z_{\text{spec}} < 1.622$ and the photometric redshifts, showing candidate members with $1.43 < z_{\text{phot}} < 1.77$, except for galaxies with $z_{\text{spec}} < 1.600$ or $z_{\text{spec}} > 1.622$. The associated surface density contours show that there are two localized overdensities: one towards the northern edge and one towards the western edge of the GMASS field. This is a striking coincidence of high density and galaxy type, consistent with density relations found at lower redshift. To make these statements more quantitative, we have defined a circular high density region (see Fig. 1), following Castellano et al. (2007), centered on a remarkably large galaxy in the centre of the northern overdensity, and with a radius of one (physical) Mpc. The high–density region contains 21 of the galaxies with $z_{\text{spec}} = 1.6$; a similar number is present in the area outside this region, which is, however, five times larger. From the six early and intermediate type-galaxies among the members, five are within the high–density region, while three more, west of the GMASS field, are known from the K20 survey (Cimatti et al. 2004).

To compare the properties of the member galaxies with field galaxies, we select a sample of 43 galaxies outside the peak, i.e., 24 in the redshift interval $1.416 < z < 1.598$ and 19 in the interval $1.624 < z < 1.840$. The field galaxies were selected within the GMASS field and have therefore similar, identically derived, information available to the galaxies in Cl 0332-2742. There are significant differences (KS test probabilities $<1\%$) for many physical properties between the galaxies in the high–density region and the field. The brightest confirmed galaxy member is located, together with two other bright galaxies in the north-east of the GMASS field. It is remarkable that this triplet of massive, passive and red galaxies lies about $1.5'$ (760 kpc) eastward of the centre of the high density region. This may be an indication that the cluster is not relaxed.

Employing the biweight statistic, we estimate a velocity dispersion for the 42 galaxies of $\sigma = 440^{+95}_{-60}$ km s$^{-1}$ and median redshift $z_{\text{med}} = 1.610$. Considering only the 21 galaxies within the high density region, we obtain a velocity dispersion of $\sigma_{\text{high}} = 500^{+100}_{-70}$ km s$^{-1}$. The distribution of the 42 redshifts is not consistent with a Gaussian distribution. Its asymmetry may be an indication that Cl 0332-2742 is not relaxed. Although we do not know whether the structure under study here is virialized, we apply the usual relations for virial radius and mass, obtaining estimates of $R_{200} = 0.5$ Mpc and $M_{\text{vir}} = 9 \times 10^{13}$ M$_{\odot}$.

To estimate the galaxy overdensity in redshift, we assume a flat $n(z)$ distribution and employ the number of 108 galaxies with spectroscopically–confirmed redshifts within the GMASS sample in the range $1.400 < z < 1.900$. We find an overdensity of $11\pm3$, where the uncertainty is determined by excluding the $z = 1.6$ galaxies in the flat $n(z)$ distribution or not. Using this overdensity and the volume defined by the GMASS field size and the redshift in-
interval $1.600 < z < 1.616$, we obtain a total mass within Cl 0332-2742 of
$6.7 \pm 1.6 \times 10^{14} M_\odot$. Considering only the volume occupied by the high
density region, and its overdensity, we obtain a total mass of $7 \times 10^{13} M_\odot$.

The field population of galaxies up to at least $z \sim 1$ shows a bimodal
distribution in colour (e.g., [Bell et al. 2004]). Within cluster populations, the
bimodality is detected as a concentration of red (early–type) galaxies on a line
in a colour-magnitude diagram (CMD) using colours which straddle the 4000 Å
break. For $z = 1.6$, the break is shifted to 1.04 μm and a suitable CMD is
therefore a plot of $z - J$ vs $J$ (Fig. 1). 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 $z - J > 1.3$. We overplot a
line that represents a theoretical red sequence at $z = 1.60$, corresponding to the
predicted $z$ and $J$ magnitudes of the stellar populations of elliptical galaxies that
formed in a burst of 0.5 Gyr at $z_f = 3.0$ (Kodama et al. 1998). This line appears
to represent very well the sequence formed by the red galaxies in Cl 0332-2742.

The structure at $z = 1.6$, described here, is most probably a galaxy cluster
progenitor: there is a galaxy overdensity of at least a factor eight, a red
sequence of passive galaxies, and evidence that the galaxies in the structure are
significantly more evolved and more massive than field galaxies. However, the
irregularity of the structure and the weak X-ray emission, suggest that the clus-
ter is not relaxed yet. These results appear to be consistent with predictions
of models of hierarchical galaxy evolution. We conclude that Cl 0332-2742 is a
galaxy cluster under assembly (see Kurk et al., submitted, for more details).

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References

S. Andreon, H. Quintana, M. Tajer, G. Galaz, & J. Surdej 2006, MNRAS 365, 915
E. F. Bell, C. Wolf, K. Meisenheimer, et al. 2004, ApJ 608, 752
H. Butcher and A. Oemler, Jr 1984, ApJ 285, 426
M. Castellano, S. Salimbeni, D. Trevese, et al. 2007, ApJ 671, 1497
A. Cimatti, M. Mignoli, E. Daddi, et al. 2002, A&A 392, 395
A. Cimatti, E. Daddi, A. Renzini, et al. 2004, Nat 430, 184
A. Cimatti, P. Cassata, L. Pozzetti, et al. 2008, A&A 482, 21
R. Fassbender, H. Boehringer, G. Lamer, et al. 2008, A&A 481, L73
R. Gilli, A. Cimatti, E. Daddi, et al. 2003, ApJ 592, 721
T. Kodama, N. Arimoto, A. J. Barger, & A. Aragón-Salamanca 1998, A&A 334, 99
T. Kodama, I. Tanaka, M. Kajisawa, et al. 2007, MNRAS 377, 1717
C. Maraston 2005, MNRAS 362, 799
P. J. McCarthy, H. Yan, R. G. Abraham, et al. 2007, ApJ 664, 17
S. A. Stanford, P. R. Eisenhardt, M. Brodwin, et al. 2005, ApJ 634, L129
S. A. Stanford, A. K. Romer, K. Sabirli, et al. 2006, ApJ 646, L13
C. C. Steidel, K. L. Adelberger, A. E. Shapley, et al. 2005, ApJ 626, 44
K.-V. H. Tran, M. Franx, G. D. Illingworth, et al. 2007, ApJ 661, 750
E. Vanzella, S. Cristiani, M. Dickinson, et al. 2005, A&A 434, 53
E. Vanzella, S. Cristiani, M. Dickinson, et al. 2006, A&A 454, 423
B. P. Venemans, J. D. Kurk, G. K. Miley, et al. 2002, ApJ 569, 11