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An overdensity of Lyman α sources at $z \sim 6.5$.

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Abstract

In a search for Ly_α sources around two bright star forming sources detected by Ouchi et al.(2010) in the SXDX field, we have detected 45 additional low luminosity Lyman emitting sources. These sources show signs of being clustered, confirming the idea that the visibility of LAEs, at or beyond the epoch of reionisation is boosted by clustering of low luminosity LAES. We have analysed these clustering and discuss its possible evolution. This would be one of the most distant overdensities ever detected. We derive a mass for this overdensity and conclude that it will evolve to become a massive cluster at $z = 0$, similar or larger in mass to the Coma cluster.

1 Introduction

The Lyα emission line galaxies (LAEs) and the prominent rest-frame UV continuum galaxies (LBGs) constitute the best tracers of star formation, within the optical-NIR window, up to the end of the cosmic re-ionization era at $z \sim 6$ [5]. There is increasing evidence that the bulk of the cosmic SFR density, and thus the ionizing photon density, required to achieve the complete re-ionization of the Universe, is due to an abundant population of low luminosity star forming galaxies [14],[3], [18]. It is also well known, that the visibility of LAEs get boosted by their clustering properties [12], [13]. We started a project with GTC, to perform the first comprehensive study of the low luminosity population of star-forming galaxies at $z = 6.5$. To maximize our probability of finding low luminosity sources, we followed the strategy proposed by [16] to check for possible proto-clusters in regions with positive density enhancement. Thus

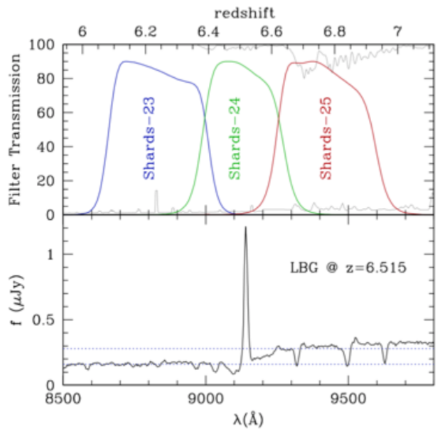

Figure 1: SHARDS filters used in the observations

the field observed included a pair of the most massive star- forming galaxies inside the large filamentary structure discovered by [15] at $z \sim 6.5$. The area surveyed corresponds to the OSIRIS FoV, i.e. roughly $8 \times 8\,\mathrm{arcmin}^2$ (or 20×20 comoving Mpc^2) and we reached down to Ly-cont. ~ 27 AB mag (or $M \leq M^* \sim 1.5\,\mathrm{mag}$). These observations have provided a sample of ~ 45 faint LAEs/LBGs candidate sources ranging in magnitude from 25.5 to 27.5 AB. We have done a careful analysis of the data, including completeness criteria, spuriousness of the sources, etc. A paper has been submitted containing the details of this analysis [4].

2 Observing Strategy

The observations were acquired with OSIRIS at the GTC, using three SHARDS[1] [17] filters, namely the SF883W35, the SF913W25 and the SF941W33. The typical seeing measured during the observations was 0.9”. The filter set up was chosen to detect faint companion galaxies at a redshift similar to that of the two fiducial Ouchi’s sources, namely in the range $6.39 < z < 6.62$. The filter arrangement (Fig. 1) ensures that the Lyman-α (Lyα) line, or the Lyman break fall within the range of the central, SF913W25, filter. To better constrain the redshift of the candidates very deep observations (see Table 1), with the SF883W17 filter, were performed.

Finally to detect possible continuum sources we included observations in the SF941W33 filter. The procedures for selecting the candidate sources, as well as the studies made to

[1] http://guaix.fis.ucm.es/~pgperez/SHARDS/

Table 1: SHARDS Filters and Exposure times of the GTC observations.

Band	Central Wavelength (angstrom)	FWHM (angstrom)	Exposure (seconds)
F883w35	8800	340	44100
F913w25	9100	280	38800
F941w33	9410	340	40700

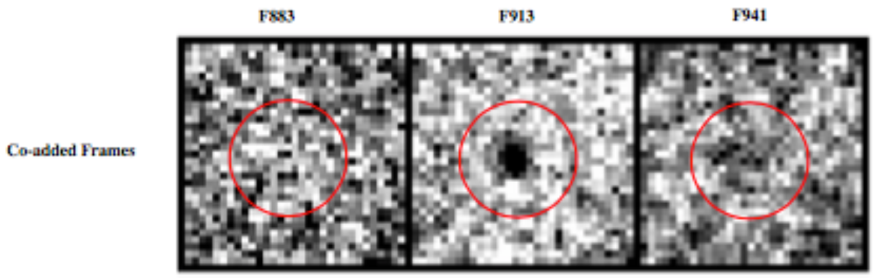

Figure 2: Stacking of the GTC observations. Note the bright spot on the central filter.

estimate completeness limits, confusion levels and probabilities of being spurious are given in Paper I. A list of 45 candidate sources was finally extracted from the observations, as it is explained in Paper I.

The sources we have found are very faint indeed. They are therefore difficult to spot against the noise in individual images, except for the brightest ones. Fig. 2 shows a stacking of the sources. In this case it can be easily seen that these sources do have an excess in the center filter, i.e. at $z \sim 6.5$.

3 An over-density of Lyman α sources at $z \sim 6.5$

3.1 The OUCHI field Luminosity Function around the two fiducial sources

A first indication that the cluster environment around these two Ouchi's sources is over-dense is given by the surface number counts. For instance, [19] give a typical figure of 0.4 sources arcmin^{-2} for sources at $z \sim 6.5$, with magnitudes in the range 26.5–27. In our case we are surveying 53.72 arcmin^2, therefore the expected mean number of sources would be $\sim 22 \pm 4.8$. The $45 + 2$ candidates found thus represent ~ 1.5 times the typical number of sources expected (taking into account the probability that $\sim 30\,\%$ of the sources may not be actual LAEs at $z = 6.5$) in a field of that extent. In Paper I, we derived the luminosity function (LF) of these LAE candidates and compared it with that of [15] for the same cosmology.

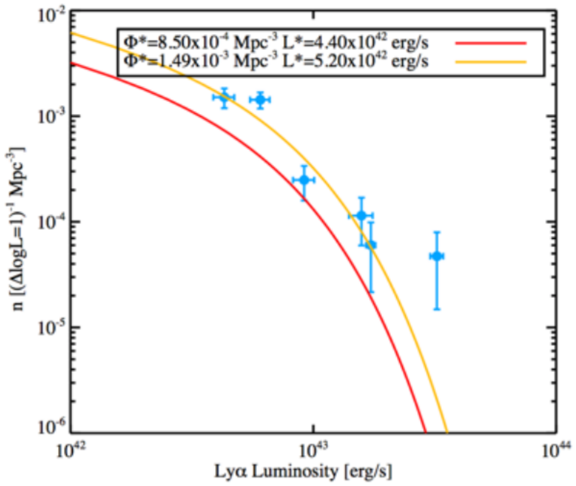

Figure 3: Luminosity Function of both the Ouchi Field and ours.

Table 2: Luminosity function parameters comparison of Ouchi's field and ours. Ouchi's LF is shown in red. Our's is shown in yellow

	Φ^* $10^{-3}\,\mathrm{Mpc}^{-3}$	L^* $10^{42}\,\mathrm{erg\,s}^{-1}$	α
Ouchi+2010	$0.85^{+0.30}_{-0.22}$	4.40 ± 0.60	-1.5 (fix)
Paper I	$\mathbf{1.30^{+0.44}_{-0.35}}$	$\mathbf{7.10+1.57_{-1.62}}$	-1.5 (fix)

The LF was fitted to a Schechter function, fixing the logarithmic slope α to the value -1.5, as found by [15], which is otherwise typical for the LF of LAE at these redshifts (Fig. 3). In what follows, all lengths will be given in comoving units. Table 1 gives the LF parameters obtained in Paper I from our sources. The Table also shows the [15] parameters, for comparison.

Notice that both Luminosity Functions are very similar, differentiating mostly in the Φ^* term. We now consider that the Ouchi LF is typical of the field, and that any difference with our LF is related to the over-density that we observe in our field. Once this assumption is taken, we can derive the density contrast of our field (Eq. 1). A further assumption has been applied here. We are assuming in this process that the matter density is proportional to the luminosity density, which is true at large scales.

$$\delta = \frac{\rho}{\bar{\rho}} - 1 = \frac{\Phi^*_{\mathrm{ours}}}{\Phi^*_{\mathrm{Ouchi}}} - 1 = 0.53^{+0.7}_{-0.6} \tag{1}$$

According to this we have an over-density $\delta = 0.53^{+0.7}_{-0.6}$, which is indeed compatible with 0, though the most probable value of the local comoving density around Ouchi's pair is $\rho = \bar{\rho}\,(1{+}\delta) = 5.95\times10^{10}\,\mathrm{M}_\odot\,\mathrm{Mpc}^{-3}$. Where $\bar{\rho}$ is the average matter density of the Universe.

Since the volumen observed through the filter SF913W25, at $z \sim 6.5$ is $6762 \pm 316\,\mathrm{Mpc}^3$, which correspond to the effective area over which all 45 LAE candidates are detected (see Paper I for further clarifications). Therefore, the most probable mass within that effective volume is $M = (4.02 \pm 0.19) \times 10^{14}\,\mathrm{M}_{\odot}$.

3.2 The evolution of the over-density trough cosmic times

Assuming the case of ellipsoidal collapse, the redshift of collapse is given by Eq. 2, resulting in $z_{\mathrm{coll}}^{\mathrm{ell}} = 2.26$ [9].

$$\delta_{\mathrm{coll}}^{\mathrm{ell}}(z_{\mathrm{coll}})/\delta = D(z_{\mathrm{coll}})/D(z = 6.5). \tag{2}$$

The mass of the galaxy cluster at the redshift of collapse (~ 2.26) is, $(4.0 \pm 0.2) \times 10^{14}\,\mathrm{M}_{\odot}$, i.e. about half of the mass $\sim 10^{15}\,\mathrm{M}_{\odot}$ of the cluster found at $z \geq 1.2$ by [6]. Our claim that the proto-cluster at $z = 6.5$ is among the most massive ones at these redshifts is thus consistent with the similar claim by [6] that the cluster they found at $z = 1.2$ is also among the most massive ones at that redshift. Only proto-clusters like ours at $z = 6.5$ with a slightly denser environment will end up at $z = 1.2$ having a mass of $\sim 10^{15}$ $\mathrm{M}_{\odot}$.

After that moment, the cluster will continue to accrete matter until $z = 0$. Although we do not know the density of the environment beyond the limits of the observed field, it should hardly be as dense as within these limits (the probability of a given value of δ rapidly drops with increasing scale). Then, according to the Extended Press-Schechter (EPS) formalism and assuming the *ConflUent System of Peak Trajectory (CUSP)* formalism, which uses the more appropriate ellipsoidal collapse, [10], [11], [7], [8], [9], the final cluster mass may be as much as $1.88 \times 10^{15}\,\mathrm{M}_{\odot}$. These values are thus similar or larger than the mass of the Coma cluster.

4 Summary

Deep GTC/OSIRIS observations in the SXDS field have provided identification for 45 new LAE candidates in the region around a pair of Star Forming galaxies discovered by Ouchi in the SXDX field at $z = 6.5$. The expected number of LAEs in this same field is 22 ± 4.8. If at least ~ 70 % of those sources turn out to be bona-fide LAEs in a followup spectrosopic survey. Such a high concentration of LAEs would represent the most distant rich over-density of galaxies observed so far. Moreover, the observed over-density cannot be much more massive than we have estimated, consistent with such massive over-densities being very rare at high redshifts.

From the most probable density contrast of ~ 0.53, we have found that the whole region of $4 \times 10^{14}\,\mathrm{M}_{\odot}$ observed at $z = 6.5$ should collapse ellipsoidally at $z = 2.26$. Assuming that the cluster then keeps growing through smooth accretion at the typical instantaneous rate predicted by the EPS (CUSP) formalism assuming ellipsoidal collapse, the final halo at $z = 0$ should reach a mass of $1.88 \times 10^{15}\,\mathrm{M}_{\odot}$, thus becoming a rich galaxy cluster rivalling the Coma cluster. Note that these masses are lower limits as we have assumed that the corresponding halo has suffered no major mergers since its collapse.

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References

[1] Baraffe, I., Chabrier, G., Gallardo, J. 2009, ApJ, 702, 27

[2] Chabrier, G., & Baraffe, I. 2007, ApJ, 661, L81

[3] Bouwens, R. J., Illingworth, G.D., Oesch, P. A., et al. 2010 ApJ 709, L137

[4] Chanchaiworawit, K., et al. 2016, MNRAS submitted (Paper I)

[5] Fan, X.; Strauss, M.A., Becker, R. H. et al. 2006, AJ, 696, 1164

[6] González V., Bouwens, R., Illingworth, G. et al. 2014, ApJ 781, 34

[7] Juan E., Salvador-Solé E., Domènec G., Manrique A., 2014, MNRAS, 439, 719

[8] Juan E., Salvador-Solé E., Domènec G., Manrique A., 2014, MNRAS, 439, 3156

[9] Juan E., Salvador-Solé E., Manrique A., 2015, submitted to MNRAS

[10] Manrique A. & Salvador-Solé E., 1995, ApJ, 453, 6

[11] Manrique A. & Salvador-Solé E., 1996, ApJ, 467, 5

[12] McQuinn, M., Hernquist, L., Zaldarriaga, M., & Dutta, S. 2007, MNRAS 381, 75

[13] Miralda-Escudé, J. 1998, ApJ, 501, 15

[14] Ouchi, M., Ono, Y. Egami, E. et al. 2009, ApJ, 723, 869

[15] Ouchi, M., Shimasaku, K., Furusawa, H., et al. 2010, ApJ, 723, 869

[16] Overzier, R.A., Shu, X., Zheng, W., et al. 2010, ApJ 704, 548

[17] Pérez-González, P. G., Cava, A., Barro, G., et al., 2013, ApJ, 762, 46

[18] Robertson, B. E., Ellis, R. S., Furlanetto, S. R. and Dunlop, J. S., 2015 ApJ 802, L19

[19] Yan, H., Windhorst, R. A., Hathi, N. P., et al. 2010, Research in A&A, 10, 867