OVERDENSITIES OF GALAXIES AT Z ~ 3.7 IN CDF-S

EUGENE KANG$^1$, MYUNGSHIN IM$^1$

ABSTRACT

We report the discovery of possible overdensities of galaxies at $z \sim 3.7$ in the Chandra Deep Field South (CDF-S). These overdensities are identified from the photometric redshift selected sample, and the $BVz$-selected sample. One overdensity is identified in the proximity of 2 AGNs and LBGs at $z = 3.66$ and $z = 3.70$ at 7-$\sigma$ significance level. The other overdensity is less significant. It is identified around six $z_{spec} \simeq 3.6$ galaxies at 3-$\sigma$ significance level. The line of sight velocity dispersions of these overdensities are found to be $\sigma_v \simeq 500 - 800$ km/sec, comparable to the velocity dispersions of clusters of galaxies today. Through the spectral energy distribution (SED) fitting, we find $\sim 15$ massive galaxies with $M > 10^{11} M_\odot$ around the $z \simeq 3.7$ overdensity. The mass of the $z \simeq 3.7$ overdensity is found to be a few $\times 10^{14} M_\odot$. Our result suggests that high redshift overdense regions can be found in a supposedly blank field, and that the emergence of massive structures can be traced back to redshift as high as $z \sim 3.7$.

Subject headings: cosmology: observations - galaxies: evolution - galaxies: clusters - galaxies: high redshift

1. INTRODUCTION

In the hierarchical galaxy formation, galaxy clusters grow through gravitational attraction of matters around high $\sigma$ peaks, and they are predicted to be rare at high redshift. Therefore, constraining the number density of high redshift clusters is an important way to test the hierarchical models (Evrard et al. 2002; Mantz et al. 2008).

Hence, many previous studies have been carried out searching for evolved structures at high redshift. Radio galaxies and AGNs are considered to be signposts for high redshift proto-clusters, and several studies have found proto-clusters at $2 < z < 4$ (Le Fèvre et al. 1996; Kurk et al. 2000; Pentericci et al. 2000; Wold et al. 2003; Kajisawa et al. 2006; Kodama et al. 2007; Venemans et al. 2007). Overdense regions are also identified out to $z \sim 6$ using galaxies selected with the Lyman break technique or narrow band imaging (e.g. Ouchi et al. 2005).

When identifying overdense regions, it is necessary to compare the overdensity with a control field which lacks notable high redshift overdense regions. For such a purpose, many studies have used the Chandra Deep Field South (CDF-S) due to the wealth of the deep multi-wavelength data over a moderately large field of view (Kajisawa et al. 2006; Kodama et al. 2007). However, a matter of concern is whether the CDF-S can really be considered as a field devoid of high redshift overdense regions. There exist a fair number of high redshift X-ray detected AGNs in CDF-S, which may harbor high redshift clusters.

Motivated by this, we searched for signs of overdensity around two AGNs at $z = 3.66$ and 3.70 separated by 2.7$^\prime$ in CDF-S, and we report the discovery of possible overdense regions at $z \sim 3.7$ in the CDF-S.

Throughout this paper, we assume a cosmology with non-zero cosmological constant (Im et al. 1997), $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$, consistent with the WMAP cosmology (Spergel et al. 2007). All magnitudes are given in the AB system.

2. SAMPLE SELECTION OF HIGH REDSHIFT GALAXY

We used two galaxy samples to identify overdense area at $z = 3.6 - 3.7$: $BVz$-selected sample, galaxies selected with photometric redshifts.

2.1. $BVz$ Selection

The Lyman break technique has been proved to be an efficient method to select galaxies at high redshift from multi-color optical data (Steidel et al. 1996). For example, Giavalisco et al. (2004b) selected B-band dropouts at $z \sim 4$ from the GOODS data. However, since the $B_{1457}$ dropout selection contains galaxies over a broad redshift range, we defined a color space optimized to select galaxies at $z \sim 3.6 - 3.7$ using the available spectroscopic redshifts including 17 at $z \simeq 3.6 - 3.7$ (Vanzella et al. 2006; Popesso et al. 2008). Figure 1 shows our selection box, overlaid on galaxies in the CDF-S field. The figure demonstrates that our selection criteria effectively filter out objects at $z < 3.55$, and at $z > 3.75$. For example, there are 18 galaxies at $z_{spec} \sim 3.47$, but only one of them makes into the $BVz$-selected sample. For the photometric data, we used the version r1.1 ACS multi-band catalog of the GOODS-team (Giavalisco et al. 2004a), and the magnitude cut of $z_{850} \leq 26.5$ mag was chosen.

With this method, we selected 245 objects over the CDF-S area of $\sim 160$ arcmin$^2$ corresponding to the surface density of $\Sigma = 1.53 \pm 0.06$ arcmin$^{-2}$ (Poisson noise).

2.2. Photometric redshifts

The $BVz$- selection is biased for UV-bright galaxies. As a complementary sample, we also selected $K$-band limited ($K_s \leq 23.8$ mag), $z \sim 3.6 - 3.7$ galaxy candidates using photometric redshift.

We estimated the photometric redshifts of the $K_s$-band limited objects using the Bayesian photometric redshift
estimation (BPZ; Benítez 2000). The photometric data include $U^∗V$/$B_{435}V_{606}/I_{775}/JHK$ bands, and the Spitzer IRAC photometry (Giavalisco et al. 2004a). The NIR photometry was performed using the version 2.0 released images in $J$, $H$, and $K_s$—band of the ESO-GOODS team (Retzlaff et al. 2008 in prep.). The depth of the VLT/ISAAC data reaches to $K = 24.7$ at the 5σ AB limits, and the simultaneous coverage in $JHK_s$-bands is 160 arcmin$^2$ after trimming the edges. To create a catalog, we ran SExtractor (Bertin & Arnouts 1996) in double-image mode, using $K_s$-band detections as a reference, and performing photometry in $J$ and $H$—bands at the $K_s$ positions. Auto-magnitudes are taken for J,H,K bands, and the Spitzer IRAC photometry. The IRAC photometry catalog was kindly provided by R. Chary (private communication). In most cases, we find IRAC detections for the K-band selected objects.

To derive photometric redshift, we used 742 SED templates with a single burst, or a constant star formation rate (SFR) or an exponentially declining SFR in the form of $SFR \propto \exp(t/\tau)$ for $\tau = 1$Gyr, 2Gyr, 3Gyr, 5Gyr, 15Gyr, or 30Gyr. These template SEDs were generated using a stellar population synthesis models of Bruzual & Charlot (2003). The metallicity was varied to be 0.4Z⊙, 1Z⊙ or 2Z⊙, and we adopted the Salpeter initial mass function extending from 0.1 to 100 $M_\odot$. The SED ages range from 100Myr to 10 Gyr or to the age of the universe at the corresponding redshift. The reddening parameter $A_V$ was allowed to change from 0 to 1.8 according to the simple two-component model of Charlot & Fall (2000). From the comparison of $z_{\text{spec}}$ versus $z_{\text{phot}}$, we find that contamination from low redshift interlopers is minimal when selecting $z \leq 3.6 - 3.7$ objects, at the redshift interval of $3.45 < z_{\text{phot}} < 3.85$. When we restrict the redshift interval as above, the scatter in the $z_{\text{phot}}$ vs $z_{\text{spec}}$ relation is about 0.1 after excluding several clear outliers. Therefore, we choose $3.45 < z_{\text{phot}} < 3.85$ as the interval for the photo-z sample selection. This gives 60 objects in total, including 17 spectroscopically confirmed galaxies with good $z_{\text{spec}}$ quality flags (B or better) at $z \approx 3.6 - 3.7$. Note that we use $z_{\text{spec}}$ instead of $z_{\text{phot}}$ when available, but restrict the spectroscopic redshift range to be $3.585 < z < 3.706$. With the photo-z selection criteria, 73% of $z_{\text{spec}} = 3.6 - 3.7$ galaxies are detected as $z = 3.6 - 3.7$ galaxy candidates. The contamination rate is 26%, but the contamination due to low redshift objects ($z_{\text{spec}} < 3.3$) is 0%. Most of the contamination comes from $z_{\text{spec}} \sim 3.5$ objects.

3. RESULTS

The overdensities were searched by running circular top-hat filters with various diameters (0.5′ to 4.8′, corresponding to 0.2 to 2 Mpc at $z = 3.7$) on the two-dimensional spatial distribution of galaxies in the above samples. The number of objects was counted around a given point within a circle with the diameter, producing a density contour map. Figure 2a shows the surface number density contour map and the location of BVz-selected sample and photo-z selected objects, respectively. Here, the contours are created using 2.4′ diameter filters, which corresponds to ~1 Mpc in physical size at $z = 3.7$. The 1 Mpc size is found to be the optimal size to identify the $z = 3.7$ overdensity (see below). The spectroscopically confirmed galaxies are plotted with squares (3.45 ≤ $z_{\text{spec}} < 3.55$), diamonds (3.55 ≤ $z_{\text{spec}} < 3.65$), triangles (3.65 ≤ $z_{\text{spec}} < 3.75$) and the open stars represent AGNs at $z_{\text{spec}} = 3.66$ and 3.70 from Szokoly et al. (2004). One density peak is apparent, located in the southern part of the CDF-S (A in Figure 2a), around $z = 3.66$, $z = 3.70$ AGNs and ($z_{\text{spec}} = 3.70$ LBGs (diamonds)) Another possible peak exists in the north around ($z_{\text{spec}} = 3.60$ LBGs (B), but its significance is much weaker.

To quantify the statistical significance of these peaks, we measured the overdensity factor as a number of $\sigma$’s from the mean surface number density by performing a Gaussian fit over the surface number density histogram. The significances of the overdensities are summarized in Table 1. The significance of the overdensity is 5-7σ for the A overdensity, demonstrating that its significance is very strong. The significance of the overdensity does not change for the top-hat filter size between 0.75 to 1.3 Mpc. Beyond these sizes, the significance decreases. On the other hand, the B overdensity has a significance of only 2-3σ.

With the limited number of spectroscopic redshifts, assigning redshifts of the overdense regions is not an easy task. Nevertheless, we find several redshifts to be plausible. The redshift distribution of CDF-S galaxies with $z_{\text{spec}}$ shows three distinct peaks at $z_{\text{spec}} \sim 3.47$, $z_{\text{spec}} \sim 3.60$, and $z_{\text{spec}} \sim 3.70$ (Figure 2c). The majority of $z_{\text{spec}} \sim 3.70$ objects are located around the overdense area A (filled histogram), as well as two AGNs at $z_{\text{spec}} = 3.70$ and 3.66, suggesting strongly that this overdensity is at $z \approx 3.7$. There are also several $z_{\text{spec}} \sim 3.47$ galaxies near the overdensity, A. However, the overdensity is more likely to be at $z \sim 3.7$, since the overdense area is clearly identified in the contour map of the BVz-sample which effectively filters out $z < 3.55$ galaxies.

Around the weak, overdense region B, we find six LBGs with $\langle z \rangle = 3.60$, and we find the 1-dimensional velocity dispersion of $\sigma_v \approx 500$ km/sec for these objects. The B
overdense region may be a loosely bound overdensity at z = 3.6.

4. DISCUSSION

4.1. Cosmic Variance

We examined whether the number of high redshift candidates is abnormally high in this field compared to other fields. For this, we examine only BVz-selected sample, since the photo-z sample does not have comparative samples readily available.

We studied the number density of BVz-selected objects in the GOODS-North field to compare with CDF-S. Using the version r1.1 ACS multi-band source catalog, we find 220 BVz-selected objects in the GOODS-North field (c.f., Giavalisco et al. 2004b). This gives the surface density $\Sigma = 1.38 \pm 0.07$ arcmin$^{-2}$, comparable to the number in CDF-S ($\Sigma = 1.53 \pm 0.06$ arcmin$^{-2}$).

We also looked for a sign of overdensity at $z \sim 3.7$ using the BVz-selected sample in the GOODS-N field. We find the most strong overdensity has the overdensity significance of $3.7\sigma$. This suggests that the GOODS-North may contain a weak overdense area at $z \sim 3.7$, but its significance is much lower than the overdense region we identified in the CDF-S.

4.2. Stellar Population

In order to find massive galaxies associated with the overdense regions, we performed SED-fittings to 60 galaxies in the photo-z sample following the procedure of Shim et al. (2007), with the SED templates used for the photometric redshift determination. Note that we have limited the SED-fitting to objects with IRAC data in order to reduce uncertainties and degeneracies arising from using only the rest-frame optical data.

In Figure 3, we show the best-fit SEDs of two representative massive galaxies at the overdense region A in CDF-S. We find 35 galaxies with $M_{\text{star}} \gtrsim 10^{11} M_\odot$ over the whole CDF-S area. More than 43% (15) of these massive objects are located within $\sim 1$ Mpc radius of the overdensity peak of the A region. This offers a further support for the existence of $z \sim 3.7$ overdensity.

We also checked the usefulness of the $H - K$ color selection of $z \sim 3.7$ as advocated by Brammer et al. (2007). They suggest that objects with $H - K > 0.9$ mag are likely to be at $\langle z \rangle = 3.7$ based on their photometric redshift analysis. However, our analysis show that only about 30% of $H - K > 0.9$ objects are at $z > 3$, for both the $z_{\text{spec}}$ and the $z_{\text{phot}}$ samples. Therefore, we conclude that the usefulness of the $H - K > 0.9$ selection method is limited.

4.3. Overdensity Mass

We estimate the overdensity mass in several different ways for the A area.

First, we estimate the overdensity mass assuming that it is a virialized structure, following Biviano et al. (2006). This assumption is not plausible, considering that the age of the universe is only 1.6 Gyr at $z = 3.7$ while it takes nearly several Gyr's for galaxies to cross the 1 Mpc structure at the given velocity dispersion. Nevertheless, the method can place a useful upper limit on the overdensity mass. For the cluster size, we use the harmonic mean radius of the photo-z selected objects within 1 Mpc radius (twice the filter size that gives the maximal overdensity signal) from the overdensity center. This gives the size of 0.55 Mpc. Assuming that the one-dimensional velocity dispersion, $\sigma_v$, of several possible proto-cluster members with $z_{\text{spec}}$ is a representative value, we estimate the cluster virial mass using the gapper estimator (Beers et al. 1990). We find that $\sigma_v = 800$ km/sec by excluding a small redshift peak at $z_{\text{spec}} = 3.66$. The derived cluster virial mass is, then, $M_{\text{vir}} \approx 5 \times 10^{14} M_\odot$.

Next, we estimate the overdensity mass applying the procedure similar to Venemans et al. (2005) on the $z_{\text{phot}}$-selected sample. Suppose that the cluster is roughly spherical, and has a 0.55 Mpc radius equivalent to the
harmonic mean radius as derived above. Using the range of 3.45 < z < 3.85 to be the interval as the selection window, we find the overdensity factor of δ_{sat} ∼ 700. Adopting the bias parameter of b = 4 of B-dropouts in CDF-S (Lee et al. 2006), we obtain the cluster mass of 4 × 10^{14} M_{⊙}.

Finally, we estimate the overdensity mass by adding up the stellar mass of the member candidates within the 0.55 Mpc radius, and converting it to the total mass assuming a M_{star}-to-M_{halo} ratio of 0.026 - 0.056 of early-type galaxies (Jiang & Kochanek 2007). Here, the overdensity mass can be expressed as M = (N_g × f × (M_{star}))/((0.026 - 0.056)M_{⊙}), where N_g and (M_{star}) is the number and the average mass of galaxies with M_{star} > 10^{11} M_{⊙}, and f is the ratio of the mass of galaxies with M > 10^{11} M_{⊙} to those with M < 10^{11} M_{⊙}. In our case, we have N_g = 6 and (M_{star}) = 5 × 10^{11} M_{⊙}. We adopt f ∼ 4, which is the ratio of the luminosity density of L > L_{*} galaxies to that of L < L_{*} galaxies in the Schechter function with the faint-end slope α ∼ −1.24 (e.g., Rines & Geller 2008). This gives the overdensity mass of (2.1 - 4.6) × 10^{14} M_{⊙}.

It is interesting that several independent mass estimates give the overdensity mass to be M ∼ a few × 10^{14} M_{⊙}. The plausible assumption of the virialization even gives the mass consistent with other estimates. This suggests that the virialization of the proto-cluster many soon be completed. However, the expected number density of halos as massive as a few × 10^{14} M_{⊙} at z ∼ 3.5 is extremely low with 10^{-10} Mpc^{-3} (Park & Kim 2007), and the probability of finding such a halo in the CDF-S is only 10^{-5}. This structure can be a part of the filaments and walls at high redshift as well. The existence of another weak overdense area such as the B overdensity supports such an idea. A careful analysis of simulation data should help us understand the nature of this kind of overdensities.

5. CONCLUSIONS

By examining the 2-dimensional distribution of 3.45 < z < 3.85 candidates in the CDF-S field selected from the photometric redshift method or the BV z color-color space, we find plausible associations of overdense region of such objects with AGNs and LBGs at z_{spec} ∼ 3.7. The significance of the overdense regions is found to be 5-7σ. The overdense area is abundant with massive galaxies, adding another support that this is a proto-cluster. The derived mass of the proto-cluster is found to be a few × 10^{14} M_{⊙}. The existence of the massive proto-cluster in CDF-S shows that one must be cautious when examining the significance of high redshift overdensities in other fields with respect to CDF-S.

REFERENCES

Beers, T. C., Flynn, K., & Gebhardt, K. 1990, AJ, 100, 32
Benitez, N. 2000, ApJ, 536, 571
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Biviano, A., et al. 2006, A&A, 456, 23
Brammer, G. B., & van Dokkum, P. G. 2007, ApJ, 654, L107
Charlot, S., Fall, S. M., 2000, ApJ, 539, 718
Evrard, A. E., et al. 2002, ApJ, 573, 7
Giavalisco, M., et al. 2004, ApJ, 600, L93
Giavalisco, M., et al. 2004, ApJ, 600, L103
Im, M., Griffiths, R. E., & Ratnatunga, K. U. 1997, ApJ, 475, 457
Jiang, G., & Kochanek, C. S. 2007, ApJ, 671, 1568
Kajisawa, M., et al. 2006, MNRAS, 371, 577
Kodama, T., et al. 2007, MNRAS, 377, 1717
Kurk, J. D., et al. 2000, A&A, 358, L1
Le Fevre, O., Delorme, J. M., Crampton, D., & Dickinson, M. 1996, ApJ, 471, L11
Mantz, A., Allen, S. W., Ebeling, H., & Rapetti, D. 2008, MNRAS, 387, 1179
Ouchi, M., et al. 2005, ApJ, 620, L1
Park, C., & Kim, J. 2007, Revista Mexicana de Astronomia y Astrofisica Conference Series, 28, 93
Pantericci, L., et al. 2000, A&A, 361, L25
Popesso, P., et al. 2008, ArXiv e-prints, 802, arXiv:0802.2930
Reed, D. S., et al. 2007, MNRAS, 374, 2
Rines, K., & Geller, M. J. 2008, AJ, 135, 1837
Shim, H., et al. 2007, ApJ, 669, 749
Overdensities at $z \sim 3.7$ in the CDF-S

Spergel, D. N., et al. 2007, ApJS, 170, 377
Steidel, C. C., Giavalisco, M., Dickinson, M., & Adelberger, K. L. 1996, AJ, 112, 352
Szikoly, G. P., et al. 2004, ApJS, 155, 271
Vanzella, E., et al. 2006, A&A, 454, 423
Venemans, B. P., et al. 2005, A&A, 431, 793
Venemans, B. P., et al. 2007, A&A, 461, 823
Wold, M., et al. 2003, AJ, 126, 1776