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Large-scale structure of short-lived Lyman α emitters

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ABSTRACT

Recently discovered large-scale structure of Lyman α emitters (LAEs) raises a novel challenge to the cold dark matter (CDM) cosmology. The structure is extended over more than 50 Mpc at redshift $z = 3.1$, and exhibits a considerably weak angular correlation. Such properties of LAE distributions appear to be incompatible with the standard biased galaxy formation scenario in the CDM cosmology. In this Letter, by considering the possibility that LAEs are short-lived events, we attempt to build up the picture of LAEs concordant with the CDM cosmology. We find that if the lifetime of LAEs is as short as $(6.7 \pm 0.6) \times 10^7$ yr, the distributions of simulated galaxies successfully match the extension and morphology of large-scale structure of LAEs at $z = 3.1$, and also the weak angular correlation function. This result implies that LAEs at $z = 3.1$ do not necessarily reside in high density peaks, but tends to be located in less dense regions, in a different way from the expectation by the standard biased galaxy formation scenario. In addition, we make a prediction for the angular correlation function of LAEs at redshifts higher than 3. It is found that the prediction deviates from that made by the standard biased galaxy formation scenario even at redshifts $4 \lesssim z \lesssim 6$.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – large-scale structure of Universe.

1 INTRODUCTION

Recently, the deep imaging surveys made by $8 \sim 10$ m class telescopes with narrow-band filters have effectively revealed the properties of Lyman α emitters (LAEs), which are one class of high-redshift objects (Cowie & Hu 1998; Hu, Cowie & McMahon 1998; Hu, McMahon & Cowie 1999; Hu et al. 2002). Based on the observational results, it is inferred that LAEs have smaller sizes, much less dust, and a smaller amount of stellar component than the other classes of high redshift galaxies, e.g. Lyman break galaxies (LBGs), at the same redshifts (Shapley et al. 2001; Venemans et al. 2005). The spatial distribution of observed LAEs generally shows large filamentary structure (Shimasaku et al. 2003; Ouchi et al. 2004, 2005; Matsuda et al. 2005). However, as pointed out by Hamana et al. (2004) recently, the observed properties of LAEs, such as weak angular correlation function (ACF), are not explained well by a standard biased galaxy formation scenario in the context of Λ cold dark matter (ΛCDM) cosmology. Especially, the large-scale structure of LAEs found by Hayashino et al. (2004) is difficult to reproduce. The large-scale structure shows a belt-like structure rather than a filamentary one, and may correspond to 6σ density fluctuation if it follows underlying dark matter distribution (Kauffmann et al. 1999). ACF is significantly weaker than that predicted in a conventional biased galaxy formation model (e.g. Kauffmann, Nusser & Steinmetz 1997). Moreover, ACF becomes negative at small scales of <180 arcsec (<6 h^{-1} Mpc) in high-density regions (HDRs; Hayashino et al. 2004). Hence, the observational features of spatial distribution of LAEs appear to be incompatible with the standard biased galaxy formation model.

From a theoretical point of view, it has recently been argued that LAEs corresponds to an early chemodynamical evolution phase of primordial galaxies (Mori & Umemura 2006a,b). In an ultra high resolution simulation of the dynamical and chemical evolution of a galaxy performed by Mori & Umemura (2006a,b), it is shown that multiple supernova explosions at an early phase of $< 3 \times 10^8$ yr result in forming high-density cooling shells, which emit such strong Lyman α as to account for the luminosity of LAEs. However, it has not been discussed whether this picture of LAEs is consistent with the observation.

In this Letter, the spatial distributions of LAEs are simulated by taking into account the lifetime of the emitters, which has not been hitherto considered in the standard biased galaxy formation scenario (Kauffmann et al. 1999; Hamana et al. 2004). Then, we investigate whether the picture of short-lived LAEs can explain the clustering properties of LAEs found by Hayashino et al. (2004). In Section 2, we describe the basic picture and numerical method. In Section 3, the

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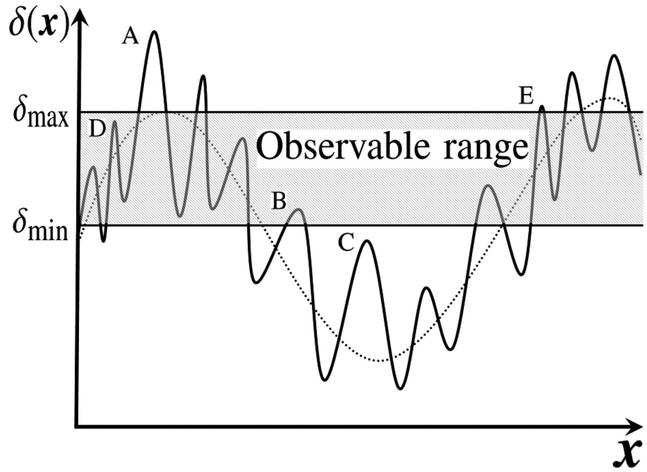

Figure 1. Schematic view of the present model. The amplitude of density fluctuations at a redshift are shown against the spatial location. The density peaks above $\delta_{\rm max}$, e.g. peak A, have already finished their lifetime as LAEs. In contrast, the density peaks below $\delta_{\rm min}$ e.g. peak C, have not yet started to shine as LAEs. The density peaks between $\delta_{\rm min}$ and $\delta_{\rm max}$, e.g. peaks B or D, can be considered as LAEs. In this view, peak A is the oldest galaxy after LAE phase. Peak B is the youngest LAEs and peak D is the oldest LAEs. Peak E has just finished to shine as a LAE at that redshift.

results are presented with some discussion. Section 4 is devoted to the summary. Throughout this Letter, we adopt ΛCDM cosmology with the matter density $\Omega_{\rm M} = 0.3$, the cosmological constant $\Omega_\Lambda = 0.7$, the Hubble constant $h = 0.7$ in units of $H_0 = 100\,{\rm km\,s^{-1}\,Mpc^{-1}}$, the baryon density $\Omega_{\rm B}\,h^2 = 0.02$, and $\sigma_8 = 0.92$ (Spergel et al. 2003).

2 MODEL

2.1 Basic picture

In Fig. 1, the schematic picture of the present galaxy formation model is presented. In the context of a conventional biased galaxy formation model, density peaks with amplitudes that exceed a minimum threshold value ($\delta_{\rm min}$ in Fig. 1) in the linear regime are identified as galaxies. In other words, only this threshold of fluctuations has been discussed as a parameter of biased galaxy formation (Kauffmann et al. 1999; Hamana et al. 2004).

Here, we introduce an additional criterion by postulating that LAEs evolve to galaxies with no strong Lyman α emission after their short lifetime. More specifically, we take the following assumptions for LAEs: (i) LAEs are galactic objects that form at the peaks of density fluctuations; (ii) LAEs are in the phase of their first starbursts; (iii) chemical evolution of LAEs results in strong attenuation of Lyman α emission due to the increase of dust, and therefore cannot be observed as LAEs after their lifetime. We incorporate this picture by setting a maximum threshold of density fluctuations ($\delta_{\rm max}$ in Fig. 1). Then, we regard the fluctuations between $\delta_{\rm min}$ and $\delta_{\rm max}$ as LAEs (a shaded region in Fig. 1). The growth time from $\delta_{\rm min}$ to $\delta_{\rm max}$ corresponds to the lifetime of LAEs. For instance, peak A in Fig. 1 is the evolved galaxy that cannot be classified as an LAE because it exceeds $\delta_{\rm max}$ at the redshift. Peaks B and D can be considered as LAEs. Peak D is the oldest LAE.

2.2 Numerical method

To compare our model with the observed clustering properties of LAEs (Hayashino et al. 2004), we numerically generate LAE distributions and estimate the two-point angular correlation function using the following procedures.

2.2.1 Generation of LAE spatial distribution

It is assumed that the dynamical evolution of baryonic matter follows that of dark matter. Density fields of dark matter are created by generating random Gaussian density fields, and the dynamical evolution is represented by a truncated Zel'dovich approximation (Sathyaprakash et al. 1995). This approximation traces the growth of density fluctuations in the linear regime, and truncates non-linear growth by suppressing the amplitude of density fluctuations that become non-linear. In the present simulation, we use k-space Gaussian window $\Pi = \exp(-k^2/2k_{\rm G}^2)$ as the truncation boundary, where $k_{\rm G}$ corresponds to the scale that just enters the non-linear stage at a redshift z. The truncated power spectrum of density fluctuation at z, $P^*(k, z)$, is written as

$$P^*(k, z) = P(k, z)\Pi^2(k, z), \quad (1)$$

where $P(k, z)$ is the power spectrum of density fluctuations at z. The wavenumber $k_{\rm i}$ and real scale $r_{\rm i}$ have the relation of $k_{\rm i} = 2\pi/r_{\rm i}$.

According to the ΛCDM theory, the physical size of the 1σ density fluctuation that collapses just at $z = 3.1$ is about $R = 1\,h^{-1}$ Mpc. In this study, we consider density fluctuations down to this physical size. In order to directly compare our model with the LAE data in the comoving volume of $(50\,h^{-1}\,{\rm Mpc})^3$ (Hayashino et al. 2004), we simulate the same comoving volume with 200^3 grids. The whole simulation box contains $4.5 \times 10^{15}\,{\rm M_\odot}$ in dark matter components, and each cell is $(0.25\,h^{-1}\,{\rm Mpc})^3$ and has $5.7 \times 10^8\,{\rm M_\odot}$ on average. Next, we make coarse-graining of density fields by comoving volume of $(1\,h^{-1}\,{\rm Mpc})^3$ which corresponds to the physical size of interest. Each coarse-grained cell has $3.6 \times 10^{10}\,{\rm M_\odot}$ in dark matter on average. The coarse-grained cells that satisfy the density fluctuation criterion, $\delta_{\rm min} \leqslant \delta \leqslant \delta_{\rm max}$, are regarded as LAEs. The positions are assumed to be the centre of mass in a coarse-grained cell.

We choose several combinations of $\delta_{\rm min}$ and $\delta_{\rm max}$. A set of $\delta_{\rm min}$ and $\delta_{\rm max}$ was constrained so that the number of simulated LAEs should match the observed number of LAEs at $z = 3.1$ (Hayashino et al. 2004). Thus, if $\delta_{\rm min}$ is set, then $\delta_{\rm max}$ is determined from the constraint of the number of LAEs. In the linear regime, only density fluctuations with $\delta \geqslant 1.7$ corresponds to collapsed objects (Peacock 1998). Therefore, we consider $\delta_{\rm min}$ larger than 1.7. Resultant three-dimensional distributions of LAEs are projected into a two-dimensional plane to compare observed angular distributions.

2.2.2 Angular correlation function (ACF)

To calculate the two-point ACF of the simulated spatial distribution of LAEs, we use the well-known estimator

$$w(\theta) = \frac{N_{\rm r}}{N_{\rm g}}\frac{\langle DD(\theta)\rangle}{\langle DR(\theta)\rangle} - 1, \quad (2)$$

(Peebles 1980; Peacock 1998) where $N_{\rm g}$ and $N_{\rm r}$ are the mean surface number density of simulated LAEs and that of randomly distributed points (RDPs), respectively. RDPs are distributed over the same area as LAEs. $\langle DD(\theta)\rangle$ is the averaged pair number of LAEs in a range of $(\theta, \theta + {\rm d}\theta)$, and $\langle DR(\theta)\rangle$ is the averaged pair number between LAEs and RDPs in a range of $(\theta, \theta + {\rm d}\theta)$. To raise the precision of statistics, we calculate ACFs for 30 different realizations of density fluctuations and average them. Then, the error on $w(\theta)$ is defined by the standard deviation of ACFs.

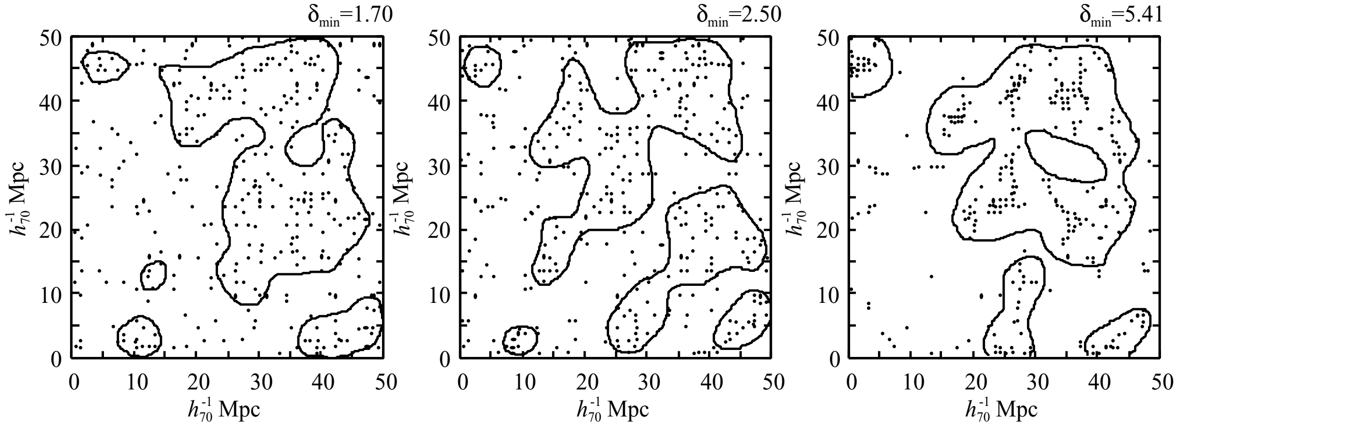

Figure 2. LAE distribution for different values of $\delta_{\min}$ and $\delta_{\max}$. the left-hand panel shows the LAE distribution for the model with $\delta_{\min} = 1.7$ and $\delta_{\max} = 1.75$, and the middle panel shows $\delta_{\min} = 2.5$ and $\delta_{\max} = 2.63$. The right-hand panel shows $\delta_{\min} = 5.4$ and $\delta_{\max} = \infty$, which corresponds to a conventional biased galaxy formation model. The contours represent high-density regions (HDRs) of LAEs under the same condition as Hayashino et al. (2004).

3 RESULTS

3.1 Clustering properties of LAEs

In Fig. 2, the spatial distributions of simulated LAEs are shown for different values of $\delta_{\min}$. The contours depict a 'high-density region' (HDR) defined under the same condition as in Hayashino et al. (2004), where the number density smoothed with a Gaussian kernel of $\sigma_{\rm G} = 90$ arcsec (corresponding to $3\,h^{-1}$ Mpc) is equal to the mean number density in the entire field. The left-hand panel in Fig. 2 is the model with $\delta_{\min} = 1.7$ and $\delta_{\max} = 1.75$, and the middle panel is the model with $\delta_{\min} = 2.5$ and $\delta_{\max} = 2.63$. In the right-hand panel, a conventional biased galaxy formation model is shown, where $\delta_{\min} = 5.4$ is assumed and all fluctuations with $\delta \geqslant \delta_{\min}$ are regarded as LAEs. In all these panels, we can recognize large-scale structures, but the clustering manners are somewhat different. The spatial distributions in the biased galaxy formation model exhibit a very strong contrast and their clustered regions are fairly isolated. On the other hand, the distributions for $(\delta_{\min}, \delta_{\max}) = (1.7, 1.75)$ or (2.5, 2.63) appear to be belt-like and less clustered, similar to the observed spatial distribution of LAEs (Hayashino et al. 2004).

In order to quantify the difference in spatial distributions, we calculate ACFs. In Fig. 3, the resultant ACFs for all the models are presented. Also, the ACF for LAEs observed in the SSA22a field (Hayashino et al. 2004) is shown. The upper and the lower panels show the ACF in the whole region and that in HDR, respectively. The results show different behaviours on scales smaller than ~ 300 arcsec. The biased galaxy formation model shows strong correlation on small scales as expected in a standard biased model (Kauffmann et al. 1999), and obviously does not match the ACF of observed LAEs in the SSA22a field. Furthermore, the model with $(\delta_{\min}, \delta_{\max}) = (2.5, 2.63)$ results in slightly stronger ACF than the observation. The model with $(\delta_{\min}, \delta_{\max}) = (1.7, 1.75)$ remarkably agrees with the ACF of LAEs in the SSA22a field. In the HDR, the ACF exhibits negative correlation in the same way as the observation. The reduction of ACF for smaller $\delta_{\min}$ is understood as follows. In the random Gaussian density fields in a ΛCDM universe, higher density peaks are more clustered, while lower density peaks are located in less dense regions which surround the highest density regions. Thus, if small $\delta_{\min}$ is adopted and the highest peaks are cut by $\delta_{\max}$, the objects of interest are located in less dense regions and accordingly the amplitude of ACF becomes smaller. Hence, the result that the model with $(\delta_{\min}, \delta_{\max}) = (1.7, 1.75)$ reproduces the observed ACF implies that LAEs at $z = 3.1$ do not reside in the highest density peaks, but are located in less dense regions.

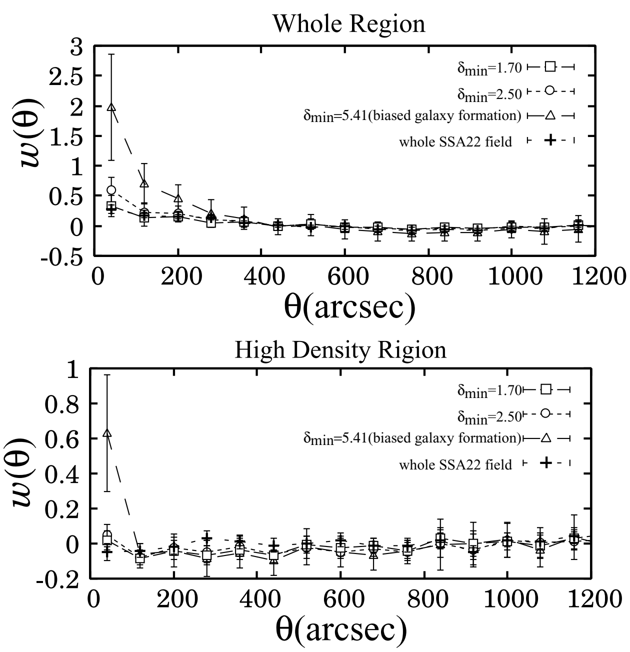

Figure 3. Two-point angular correlation functions (ACFs) of LAE distributions for each model. Upper and lower panels show ACFs in the whole region and in HDR, respectively. Open squares represent ACFs for $\delta_{\min} = 1.7$ and $\delta_{\max} = 1.75$, and open circles for $\delta_{\min} = 2.5$ and $\delta_{\max} = 2.63$. Open triangles represent ACFs for $\delta_{\min} = 5.4$ and $\delta_{\max} = \infty$, which is corresponding to a biased galaxy formation model. Crosses are ACFs of LAEs observed in SSA22a (Hayashino et al. 2004). Note that the upper panel is different from the lower panel in the scale of vertical axis.

Observationally, LAEs have been discovered around known overdensities that generally indicate strong correlations such as protocluster regions including massive galaxies such as radio galaxies (Steidel et al. 2000; Hayashino et al. 2004; Venemans et al. 2005). The observed overdensities may correspond to the situation shown in the right-hand panel of Fig. 2 and the observed LAEs correspond to the left-hand panel of Fig. 2. In that sense, the results here look consistent with these observational features. Hence, the picture in this Letter can explain not only a correlation function but also other clustering properties of LAEs such as the morphology of HDR and the environment where LAEs at $z \sim 3$ are discovered. According to recent large surveys such as SDSS, ACFs of late-type galaxies show weaker correlation compared with that of early-type galaxies at $z \lesssim 0.1$ (Zehavi et al. 2002). That is to say, as is well known, late-type galaxies are located at lower density fields. As shown here, LAEs at $z = 3.1$ should be located in less dense regions. Hence, it is suggested that a large fraction of LAEs at $z = 3.1$ may be the precursors of late-type galaxies.

3.2 Lifetime of LAEs

As shown above, $\delta_{\rm min} = 1.7$ gives the best-fittng model to account for the observed ACF. As $\delta = 1.7$ is a critical amplitude for a fluctuation to collapse (Peacock 1998), we can conclude that LAEs begin to shine just after the collapse. In other words, LAEs should be in the first phase of galaxy evolution. Because the model with $(\delta_{\rm min}, \delta_{\rm max}) = (1.7, 1.75)$ agrees with the observed ACF at $z = 3.1$, LAEs are thought to shine during the growth time from $\delta_{\rm min}$ to $\delta_{\rm max}$. The fluctuation with $\delta_{\rm max}$ at $z = 3.1$ collapses at a higher redshift $z_{\rm coll}$ when the amplitude exceeds $\delta_{\rm min}$. Hence, the lifetime of LAEs can be assessed by the cosmic time between $z = 3.1$ and $z_{\rm coll}$, which is 6.7×10^7 yr. Here, there is a small uncertainty in this estimation. When $\delta_{\rm min}$ is chosen, $\delta_{\rm max}$ is determined to match the number of observed LAEs. Because we generate random numbers to produce density fluctuations, a different set of random numbers results in a slight difference in $\delta_{\rm max}$. For the model of $\delta_{\rm min} = 1.7$, we have $\delta_{\rm max} = 1.75 \pm 0.01$ as a result of 30 different realizations. Then, the lifetime of LAEs is estimated to be $(6.7 \pm 0.6) \times 10^7$ yr. Similarly, for the model of $\delta_{\rm min} = 2.5$, we have $\delta_{\rm max} = 2.63 \pm 0.02$. Then, the lifetime is slightly longer as $(2.0 \pm 0.4) \times 10^8$ yr.

This result on LAE lifetime agrees nicely with an upper limit that is argued by realistic numerical simulations for galactic evolution (Mori & Umemura 2006a,b).

3.3 Luminosities of LAEs

We also calculate Lyman α luminosities of simulated LAEs, using an evolutionary spectral synthesis code PEGASE (Fioc & Rocca-Volmerange 1997). As a result, we have found that evaluated Lyman α luminosities match those of observed LAEs ($L_{\rm Ly\alpha} \sim 10^{42-43}$ erg s^{-1}) (Hayashino et al. 2004; Matsuda et al. 2004; van Breukelen, Jarvis & Venemans 2005). In this Letter, density fields are coarse-grained by a scale of 1 h^{-1} Mpc which corresponds to 1σ density fluctuations in the ΛCDM cosmology. If a smaller scale is taken, intrinsic Lyman α luminosities fall short of 10^{42} erg s^{-1} during Lyman α bright phase. For instance, if a coarse-graining scale is 0.25 h^{-1} Mpc, intrinsic Lyman α luminosities are $\sim 10^{41}$ erg s^{-1}. On the other hand, if a scale larger than 1 h^{-1} Mpc is taken, the number of collapsed objects is not enough to account for the observed LAE number. Hence, 1σ density fluctuations are favourable to explain the observations.

3.4 ACF of LAEs at $3 < z < 6$

By assuming the best-fiting model ($\delta_{\rm min} = 1.7$ and $\delta_{\rm max} = 1.75$), we can predict ACFs of LAEs at higher redshifts. In Fig. 4, the prediction of ACFs at redshifts of 3.1, 4.0, 5.0 and 6.0 are presented. A biased galaxy formation model is also presented, where the number of objects is scaled as to be the same as that in the best-fiting model. The $\delta_{\rm min}$ of the biased galaxy formation model at each redshift is $\delta_{\rm min} = 4.2$ at $z = 4$, $\delta_{\rm min} = 3.5$ at $z = 5$ and $\delta_{\rm min} = 2.8$ at $z = 6$, respectively. As seen in Fig. 4, the ACF of the best-fiting model approaches that of the biased galaxy formation model at higher redshifts. In other words, a larger fraction of collapsed objects shine as LAEs at higher redshifts. However, it is worth noting that there is still a noticeable difference between the best-fiting model and a biased galaxy formation model even at $z = 6$. It implies that a certain fraction has already been extinguished, so that they are not detected as LAEs.

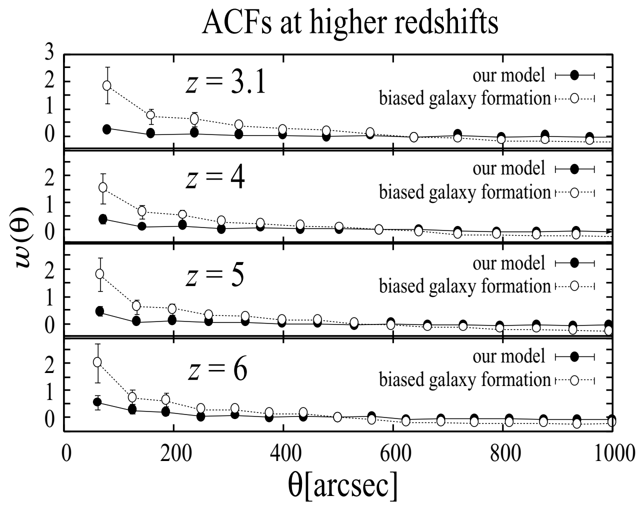

Figure 4. Two-point ACFs of simulated LAEs at redshifts $z = 3.1$, 4.0, 5.0 and 6.0. Open circles show the short-lived LAE model, while filled circles are biased galaxy formation models. In the short-lived LAE model, density peaks between $\delta_{\rm min} = 1.7$ and $\delta_{\rm max} = 1.75$ are regarded as LAEs. In the biased galaxy formation model, the number of objects is scaled as to be the same as that in the short-lived LAE model. Thus $\delta_{\rm min}$ is set to 5.4, 4.2, 3.5 and 2.8 at $z = 3.1$, $z = 4$, $z = 5$ and $z = 6$, respectively.

4 SUMMARY

To account for the recently discovered large-scale structure of LAEs at $z = 3.1$ (Hayashino et al. 2004), we have introduced a novel picture for LAEs by focusing on the lifetime of emitters. We have simulated the spatial distributions of collapsed objects by generating random Gaussian fluctuations based on the truncated Zel'dovich approximation in the ΛCDM cosmology. We have found that a conventional biased galaxy formation model is not reconciled with the observed correlation function of LAEs. If the highest peaks above $\delta = 1.75$ are cut and mild peaks between $\delta = 1.7$ and $\delta = 1.75$ are regarded as LAEs, the clustering properties, including the two-point ACF, agree quite well with the observation. Lyman α luminosities also match those of observed LAEs. The growth time from $\delta = 1.7$ to $\delta = 1.75$ can be translated into the lifetime of LAEs, which is assessed to be $(6.7 \pm 0.6) \times 10^7$ yr. A fluctuation with $\delta = 1.7$ corresponds to an object that just collapses at the redshift. Thus, LAEs are thought to be in the early evolutionary phase of galaxies, which is consistent with a recent theoretical prediction (Mori & Umemura 2006a,b). We have also predicted the correlation function at redshifts higher than 3 in the picture of short-lived LAEs. It is suggested that a certain fraction of young galaxies have already ended the LAE phase even at redshift $z = 6$.

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REFERENCES

Cowie L. L., Hu E. M., 1998, AJ, 115, 1319
Dawson S. et al., 2004, ApJ, 617, 707
Fioc M., Rocca-Volmerange B., 1997, A&A, 326, 950
Hamana T., Ouchi M., Shimasaku K., Kayo I., Suto Y., 2004, MNRAS, 347, 813
Hayashino T. et al., 2004, AJ, 128, 2073
Hu E. M., Cowie L. L., McMahon R. G., 1998, ApJ, 502, L99
Hu E. M., McMahon R. G., Cowie L. L., 1999, ApJ, 522, L9
Hu E. M., Cowie L. L., McMahon R. G., Capak P., Iwamuro F., Kneib J.-P., Maihara T., Motohara K., 2002, ApJ, 568, L75
Kauffmann G., Nusser A., Steinmetz M., 1997, MNRAS, 286, 795
Kauffmann G., Colberg J. M., Diaferio A., White S. D. M., 1999, MNRAS, 307, 529
Matsuda Y. et al., 2004, AJ, 128, 569
Matsuda Y. et al., 2005, ApJ, 634, L125
Mori M., Umemura M., 2006a, New Astron. Rev., 50, 199
Mori M., Umemura M., 2006b, Nat, 440, 644
Ouchi M. et al., 2003, ApJ, 582, 60
Ouchi M. et al., 2004, ApJ, 611, 660
Ouchi M. et al., 2005, ApJ, 620, L1
Peacock J. A., 1998, Cosmological Physics. Cambridge Univ. Press, Cambridge
Peebles P. J. E., 1980, The Large-Scale Structure in the Universe. Princeton Univ. Press, Princeton
Sathyaprakash B. S., Sahni V., Munshi D., Pogosyan D., Melott A. L., 1995, MNRAS, 275, 463
Shapley, A. E., Steidel C. C., Adelberger K. L., Giavalisco M., Dickinson M., Pettini M., 2001, ApJ, 562, 95
Shimasaku K. et al., 2003, ApJ, 586, L111
Spergel D. N. et al., 2003, ApJS, 148, 175
Steidel C. C., Adelberger K. L., Shapley A. E.. Pettini M., Dickinson M., Giavalisco, M ., 2000, ApJ, 532, 170
van Breukelen C., Jarvis M. J., Venemans B. P., 2005, MNRAS, 359, 895
Venemans B. P. G. et al., 2005, A&A, 431, 793
Zehavi I. et al., 2002, ApJ, 571, 172