

Two types of Lyman α emitters envisaged from hierarchical galaxy formation

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Accepted 2010 March 30. Received 2010 March 12; in original form 2009 August 4

ABSTRACT

In the last decade, numerous Lyman α (Ly α) emitters (LAEs) have been discovered with narrow-band filters at various redshifts. Recently, multiwavelength observations of LAEs have been performed and revealed that while many LAEs appear to be young and less massive, a noticeable fraction of LAEs possess much older populations of stars and larger stellar mass. How these two classes of LAEs are concordant with the hierarchical galaxy formation scenario has not been understood clearly so far. In this paper, we model LAEs by three-dimensional cosmological simulations of dark halo merger in a Λ cold dark matter (Λ CDM) universe. As a result, it is shown that the age of simulated LAEs can spread over a wide range from 2×10^6 to 9×10^8 yr. Furthermore, we find that there are two types of LAEs, in one of which the young half-mass age is comparable to the mean age of stellar component, and in the other of which the young half-mass age is appreciably shorter than the mean age. We define the former as Type 1 LAEs and the latter as Type 2 LAEs. A Type 1 LAE corresponds to early starburst in a young galaxy, whereas a Type 2 LAE does to delayed starburst in an evolved galaxy, as a consequence of delayed accretion of a subhalo on to a larger parent halo. Thus, the same halo can experience a Type 2 LAE phase as well as a Type 1 LAE phase in the merger history. Type 1 LAEs are expected to be younger than 1.5×10^8 yr, less dusty and less massive with stellar mass $M_{\text{star}} \lesssim 5 \times 10^8 M_{\odot}$, while Type 2 LAEs are older than 1.5×10^8 yr, even dustier and as massive as $M_{\text{star}} \sim 5 \times 10^8 - 3 \times 10^{10} M_{\odot}$. The fraction of Type 2s in all LAEs is a function of redshift, which is less than 2 per cent at $z \gtrsim 4.5$, ~ 30 per cent at redshift $z = 3.1$ and ~ 70 per cent at $z = 2$. Type 2 LAEs can be discriminated clearly from Type 1s in two-colour diagrams of $z' - H$ versus $J - K$. We find that the brightness distribution of Ly α in Type 2 LAEs is more extended than the main stellar component, in contrast to Type 1 LAEs. This is not only because delayed starbursts tend to occur in the outskirts of a parent galaxy, but also because Ly α photons are effectively absorbed by dust in an evolved galaxy. Hence, the extent of Ly α emission may be an additional measure to distinguish Type 2 LAEs from Type 1 LAEs. The sizes of Type 2 LAEs range from a few tens to a few hundreds kpc. At lower redshifts, the number of more extended, older Type 2 LAEs increases. Furthermore, it is anticipated that the amplitude of angular correlation function for Type 2 LAEs is significantly higher than that for Type 1 LAEs, but comparable to that for Lyman break galaxies (LBGs). This implies that LBGs with strong Ly α line may include Type 2 LAEs.

Key words: galaxies: evolution – galaxies: formation.

1 INTRODUCTION

To explore the early evolutionary phases of galaxies, it is important to understand galaxy formation. Partridge & Peebles (1967) pre-

dicted that the starbursts in primeval galaxies emit significant Lyman α (Ly α) emission through the recombination of ionized hydrogen in interstellar matter. Although many surveys attempted to discover such Ly α emitting galaxies (Ly α emitters, hereafter LAEs), but did not succeed to find them for a long time. In late 1990s, Cowie & Hu (1998) discovered LAEs with narrow-band filters for the first time. Currently, numerous LAEs have been discovered at high redshifts

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$3 < z < 7$ by 8–10 m class telescopes with narrow-band filters (Hu, Cowie & McMahon 1998; Hu, McMahon & Cowie 1999; Hu et al. 2002; Kodaira et al. 2003; Shimasaku et al. 2003, 2006; Hayashino et al. 2004; Matsuda et al. 2004, 2005; Ouchi et al. 2004, 2005; Taniguchi et al. 2005). Although the number of observed LAEs increases constantly, the nature of LAEs is still veiled. Recently, surveys of LAEs in the various wavelength bands (optical, infrared, submm, etc.) have been performed actively (Finkelstein et al. 2007, 2009a; Matsuda et al. 2007; Lai et al. 2008; Uchimoto et al. 2008; Tamura et al. 2009), and have revealed that while many LAEs appear to be young and less massive, a noticeable fraction of LAEs possess much older stellar populations and larger stellar mass. We have not well understood how such two classes of LAEs are concordant with the hierarchical galaxy formation scenario. As for the physical origin of Ly α emission, the cooling radiation from a primordial collapsing cloud (Haiman, Spaans & Quataert 2000; Fardal et al. 2001), from a galactic wind-driven shell (Taniguchi & Shioya 2000), or from star-forming clouds in a young starburst galaxy (Mori, Umemura & Ferrara 2004) has been considered.

Recently, Mori & Umemura (2006) proposed a galaxy evolution scenario from LAEs to Lyman break galaxies (LBGs), based on a supernova-dominated starburst galaxy model. In this scenario, LAEs correspond to an early evolutionary phase of $< 3 \times 10^8$ yr. Furthermore, Shimizu, Umemura & Yonehara (2007) have constructed an analytic model of LAEs in a Λ cold dark matter (Λ CDM) universe, and found that if LAEs form in relatively low-density regions of the universe and the duration of starburst is as short as 0.7×10^8 yr, the spatial distributions match the weak angular correlation function of LAEs observed at $z = 3.1$. The spectral energy distribution (SED) fitting for observed LAEs has shown that LAEs mostly have young average age ($\sim 10^8$ yr), low stellar mass (10^8 – $10^9 M_\odot$) and are less dusty or dust free (Gawiser et al. 2006; Finkelstein et al. 2007; Lai et al. 2008). These young LAEs are consistent with the picture by Mori & Umemura (2006) and Shimizu et al. (2007). Very recently, deep surveys of LAEs allow us to study detailed properties of individual LAEs. As a result, it has been revealed that LAEs have a wide range of age (10^6 – 10^9 yr), stellar mass (10^6 – $10^{10} M_\odot$) and dust extinction with A_V up to 1.3 mag (Finkelstein et al. 2007, 2009a; Lai et al. 2008). LAEs detected in rest-frame optical/near-infrared (NIR) bands tend to have older age, larger stellar mass and stronger dust extinction than LAEs undetected in those bands. Thus the picture of purely young starburst galaxies is not always reconciled with observed LAEs. So far, the physical reason has not been clarified for the existence of an old, massive and dusty population of LAEs. The previous study has shown that a starburst-dominated galaxy can emit strong Ly α radiation in dust-free or less dusty environments (Mori & Umemura 2006). However, starburst galaxies cannot be always LAEs in dusty environments (e.g. ultraluminous infrared galaxies). Hence, what physical state corresponds to an old population of LAEs is an issue of great significance. Some authors argue that the clumpy distributions of dusty gas is important for the transfer of Ly α photons (Neufeld 1991; Hansen & Oh 2006; Finkelstein et al. 2009b). Since Ly α photons undergo resonant scattering on the surface of gas clumps, photons can easily escape from the clumpy media. Such an effect provides the possibility of old, massive and dusty LAEs.

In this paper, we explore how a young and old population of LAEs are concordant with a hierarchical galaxy formation paradigm. For the purpose, we perform tree-dimensional cosmological simulations of dark halo merger in a Λ CDM universe, incorporating the prescriptions of star formation, spectral evolution and dust extinction.

Throughout this paper, we adopt Λ CDM cosmology with the matter density $\Omega_M = 0.3$, the cosmological constant $\Omega_\Lambda = 0.7$, the Hubble constant $h = 0.7$ in units of $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, the baryon density $\Omega_B h^2 = 0.02$ and $\sigma_8 = 0.92$ (Spergel et al. 2003).

2 MODEL AND NUMERICAL METHOD

2.1 Basic model

To pursue the star formation history in the hierarchical galaxy formation, we simulate the merging history of subgalactic haloes (hereafter subhalo) by three-dimensional cosmological N -body simulations. Here, each particle is regarded as a subhalo that is supposed to consist of dark matter and baryons. We simulate $N = 256^3$ subhaloes in a comoving volume of $(50 \text{ Mpc})^3$. The mass of a subhalo is $2.73 \times 10^8 M_\odot$. It is assumed that the star formation is triggered when a subhalo accretes on to a parent halo. Then we trace the stellar evolution separately for individual subhaloes using a spectral synthesis code ‘PEGASE’ (Fioc & Rocca-Volmerange 1997). Moreover, we take into account the effect of dust extinction on Ly α emission. The present approach allows us to analyse the distributions of star-forming regions in a halo, and also the clustering properties of haloes.

There are basically two types of subhalo accretion. One is the almost contemporaneous accretion of subhaloes in a young small parent halo, and then coeval starbursts take place in the halo. The other is the delayed accretion on to an evolved massive halo, and then a newly triggered starburst and an old stellar population coexist. Both types have the potentiality of becoming LAEs. If they satisfy LAE conditions (see the detail below), we call the former Type 1 LAEs and the latter Type 2 LAEs. A schematic view of Type 1 and Type 2 LAEs is shown in Fig. 1.

2.2 Numerical method

We perform a cosmological N -body simulation with the particle–particle–particle–mesh (P^3M) algorithm (Hockney & Eastwood 1981). The numerical scheme is based on Yoshikawa, Jing & Suto (2000). The size of comoving simulation box (L_{box}) is set to be the same as the size of LAE survey at $z = 3.1$ by Hayashino et al. (2004), that is, 50 Mpc in linear scale. This allows us to adjust LAE conditions by directly comparing with the observation. Here, the periodic boundary condition is imposed. We use the Plummer softening function for gravitational force, with the softening length of $\epsilon_{\text{grav}} = L_{\text{box}}/(10N^{1/3})$ (~ 20 kpc in a comoving scale).

A parent halo is found using a friends-of-friends algorithm (Davis et al. 1985) with linking length equal to 0.2 of the mean particle separation. In this study, a system with $\geq 2.7 \times 10^{10} M_\odot$ (say, equal to or more than 100 particles) is identified as a parent halo so that the system mass would be corresponding to observed LAEs. As previously mentioned, each particle (subhalo) in a parent halo has individual age. It is assumed that the star formation is triggered when a subhalo accretes on to a parent halo. The star formation occurs only in the subhalo, and therefore no star formation is triggered at the central of host halo. Furthermore, a subhalo which underwent the star formation once does not trigger the star formation again. Here, the star formation in each subhalo is assumed to occur at the rate as

$$\psi(t) = f_{\text{eff}} \exp\left(-\frac{t}{\tau_s}\right). \quad (1)$$

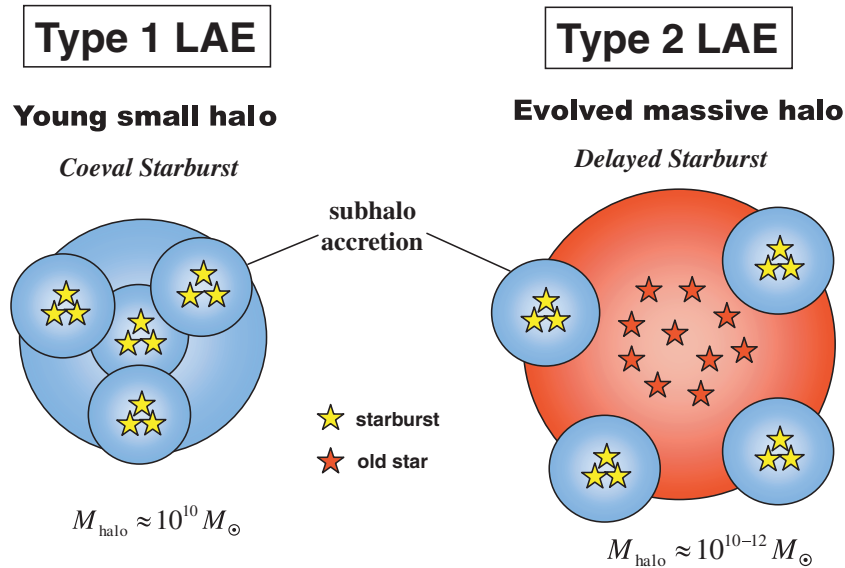


Figure 1. Basic conception of a Type 1 and Type 2 LAE. A Type 1 LAE is an early phase of coeval starbursts in a young small halo. A Type 2 LAE corresponds to delayed starbursts in an evolved massive halo.

The star formation time-scale τ_s is set to match the typical lifetime of young LAEs predicted by Mori & Umemura (2006) and Shimizu et al. (2007), that is, 1.0×10^8 yr. The efficiency f_{eff} is determined so that the final fraction of stellar mass to total baryonic mass is 10 per cent. Here, the Salpeter initial mass function is assumed. In the present model, each particle is supposed to consist of dark matter and baryons. As far as the model LAEs concerned, newly accreted subhaloes are predominantly responsible for Ly α emission, and those subhaloes emit the bulk of UV photons before their dynamical relaxation. None the less, two-component (dark matter and baryon) simulations are very worth investigating in the future work.

We identify LAEs under the same conditions as Hayashino et al. (2004), that is, $L_{\text{Ly}\alpha, \text{obs}} \geq 1.4 \times 10^{42} \text{ erg s}^{-1}$ and $\text{EW}_{\text{rest}} \geq 20 \text{ \AA}$, where $L_{\text{Ly}\alpha}$ and EW_{rest} are observed Ly α luminosity and Ly α equivalent width at rest frame, respectively. We estimate observed Ly α luminosity by

$$L_{\text{Ly}\alpha, \text{obs}} = f_{\text{esc}} L_{\text{Ly}\alpha, \text{int}}, \quad (2)$$

where $L_{\text{Ly}\alpha, \text{int}}$ is intrinsic Ly α luminosity, and f_{esc} is the escape fraction of Ly α photons. We calculate $L_{\text{Ly}\alpha, \text{int}}$ using ‘PEGASE’ (Fioc & Rocca-Volmerange 1997). The escape fraction is evaluated in terms of dust extinction as

$$f_{\text{esc}} = \exp(-\tau_{\text{dust}}), \quad (3)$$

where τ_{dust} is the line-of-sight optical depth of dust with opacity in proportion to local metallicity. In practice, τ_{dust} is dependent on grain size distributions, which are not well known in high- z objects. Hence, we normalize the net cross-section of dust grains so that the number of simulated LAEs should match the observed number of LAEs at $z = 3.1$ (Hayashino et al. 2004). (In the present analysis, dust is treated as a pure absorber of Ly α photons, and the scattering of Ly α photons is not solved. The treatment of dust extinction can be more sophisticated in the future analysis.)

3 RESULTS

3.1 Two types of simulated LAEs

In Fig. 2, the distributions of mass-weighted age are shown for simulated LAEs. The ages spread widely from 2×10^6 to 9×10^8 yr. Interestingly, a significant number of LAEs are much older than $\approx 10^8$ yr, that is, the lifetime of young LAEs predicted by Mori & Umemura (2006) and Shimizu et al. (2007). As seen in Fig. 2, the distributions are fairly continuous from younger LAEs to older ones. Younger LAEs are early coeval starburst galaxies, while older LAEs result from delayed starbursts triggered by later subhalo accretion on to evolved haloes. In order to discriminate delayed starbursts from coeval young starbursts, we plot the young half-mass ages against the mass-weighted mean ages in Fig. 3, where the young half-mass age is defined as the mass-weighted age of the young

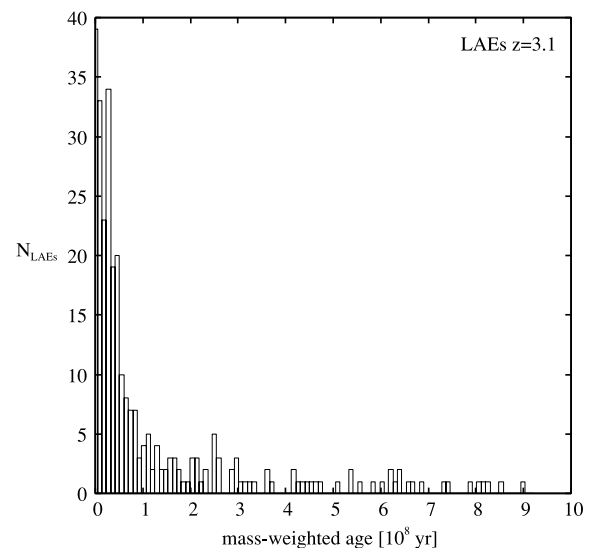


Figure 2. Age distributions of simulated LAEs. The age is defined by the mass-weighted age.

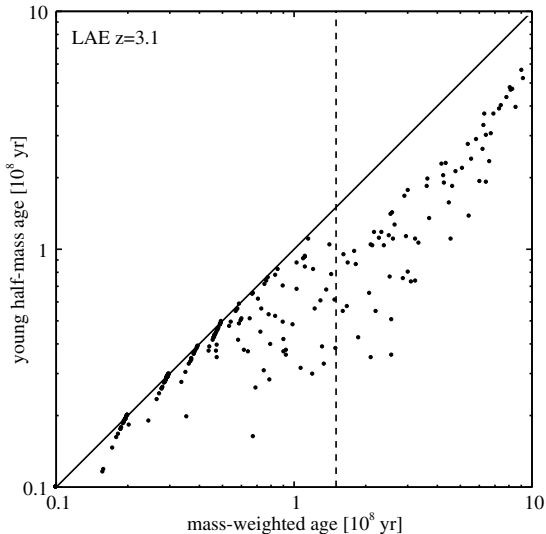


Figure 3. Young half-mass ages against mass-weighted mean ages. The straight line denotes the equality of two age definitions. A vertical dashed line shows 1.5×10^8 yr. We define LAEs younger than 1.5×10^8 yr as Type 1s, and older ones as Type 2s.

half subhaloes included in a host halo. If starbursts are coeval in a halo, young half-mass ages should be comparable to mean ages. It is clearly seen in Fig. 3 that in the part older than $\sim 1.5 \times 10^8$ yr, coeval starbursts disappear and only delayed starbursts appear to be taking place. Hence, in this paper, we define LAEs younger than 1.5×10^8 yr as Type 1 LAEs, and older ones as Type 2 LAEs. It is noted that there is not a clear boundary of two classes at 1.5×10^8 yr, but the transition is actually gradual in the sense that coeval and delayed starbursts are blended around $\approx 10^8$ yr. Nevertheless, as shown below, we find distinctive trends in photometric properties between Type 1s and Type 2s defined here.

Fig. 4 shows EW of Ly α emission, Ly α luminosity, star formation rate and stellar mass against the mass-weighted age for simulated LAEs. EW decreases with ages for Type 1 LAEs, ranging from 40 to 200 Å, although some are at a level of 350–400 Å. EW for Type 2s is randomly distributed in the range of 30–150 Å. Ly α luminosity is basically in proportion to star formation rate for Type 1 LAEs, and gradually decreases with ages. For Type 2 LAEs, Ly α luminosity randomly spread in the range of $\sim 2 \times 10^{42}$ to $\sim 2 \times 10^{43}$ erg s $^{-1}$. Interestingly, in old Type 2 LAEs ($> 6 \times 10^8$ yr), a high star formation rate does not always lead to high Ly α luminosity. This can be understood by the effect of dust extinction as argued below.

The stellar mass M_{star} of LAEs is a fairly monotonic function of age. Type 1 LAEs are less massive with $M_{\text{star}} \lesssim 5 \times 10^8 M_{\odot}$, while Type 2s are as massive as $M_{\text{star}} \sim 5 \times 10^8 - 3 \times 10^{10} M_{\odot}$. Recent observations show that LAEs detected by rest-frame optical/NIR bands are more massive than $10^9 M_{\odot}$ and pretty older (Finkelstein et al. 2007, 2009a; Matsuda et al. 2007; Lai et al. 2008; Uchimoto et al. 2008). Such objects may correspond to Type 2 LAEs.

The fraction of Type 2 LAEs in all LAEs is predicted to be a function of redshift. Fig. 5 represents the Type 2 LAE fraction against redshift. Obviously, the Type 2 fraction increases with decreasing redshift. At $z \gtrsim 4.5$, the Type 2 fraction is less than 2 per cent, since massive haloes have not grown yet, whereas it is ~ 30 per cent at redshift $z = 3.1$ and ~ 70 per cent at $z = 2$. This trend is concordant with the recent observations by Nilsson et al. (2009).

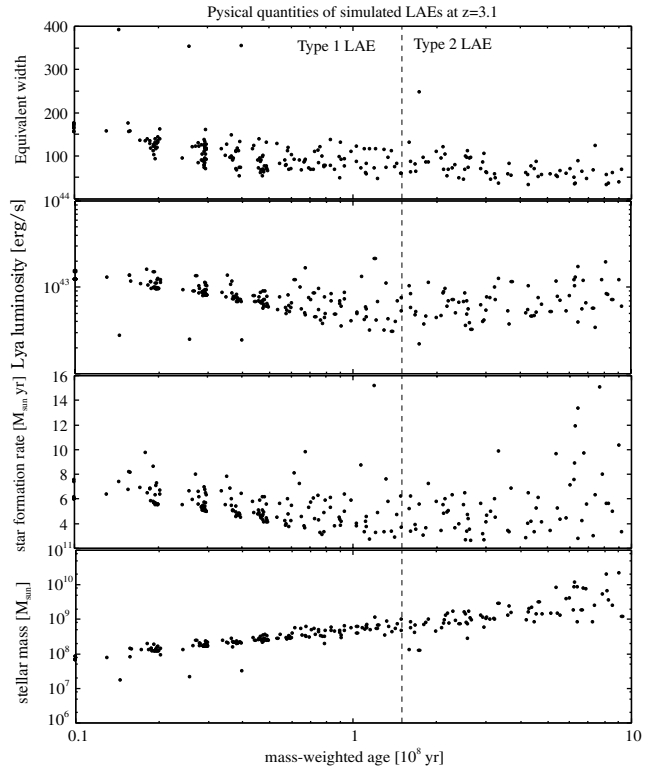


Figure 4. EW, Ly α luminosity, star formation rate and stellar mass against the mass-weighted age for simulated LAEs. A vertical dashed line shows 1.5×10^8 yr.

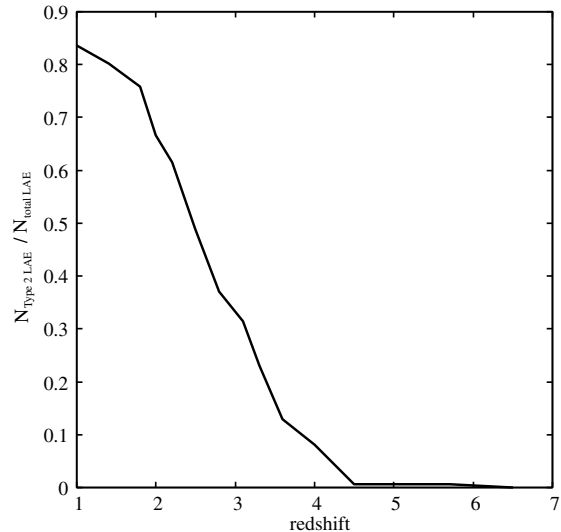


Figure 5. The fraction of Type 2 LAEs at $1 < z < 7$. The fraction is defined by $N_{\text{Type 2 LAEs}}/N_{\text{total LAEs}}$, where $N_{\text{Type 2 LAEs}}$ and $N_{\text{total LAEs}}$ are the number of Type 2 LAEs and all simulated LAEs, respectively.

3.2 Spectrophotometric properties of simulated LAEs

In Fig. 6, we show SEDs of a typical Type 1 and Type 2 LAE, which are calculated by ‘PEGASE’ (Fioc & Rocca-Volmerange 1997). A Type 1 LAE is composed of young stars, while the host galaxy of a Type 2 LAE is dominated by evolved stars, where a distinct 4000 Å break is seen. Accordingly, the colours of two types of LAEs are different.

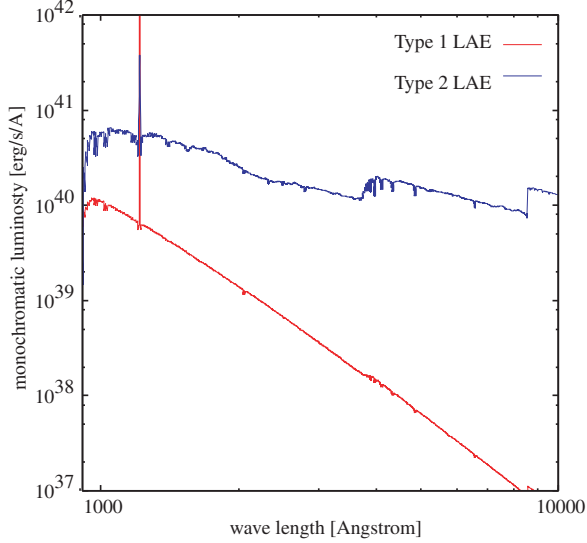


Figure 6. SEDs of a typical Type 1 and Type 2 LAE. A red line represents Type 1 and a blue line does Type 2.

In Fig. 7, two-colour diagrams are shown in observed frames for $z = 2$ LAEs and $z = 3.1$ LAEs. The upper two panels are $z' - H$ versus $J - K$, while the lower two panels are $z' - K$ versus $J - K$, where z' band is $\approx 9000 \text{ \AA}$, J band $\approx 12\,000 \text{ \AA}$, H band $\approx 17\,000 \text{ \AA}$ and K band $\approx 22\,000 \text{ \AA}$. A red line in each panel indicates the

evolutionary track of stars born in a single starburst. Therefore, LAEs near this line represent almost coeval starbursts. The mass-weighted ages are shown by colours. As expected, Type 1 LAEs ($\leq 1.5 \times 10^8 \text{ yr}$) well follow the single starburst track, whereas colours of Type 2s are a function of redshift. At lower redshifts, Type 2s deviate farther from the single starburst track. Fig. 7 shows that Type 1 and Type 2 LAEs are discriminated more clearly in the diagram of $z' - H$ versus $J - K$, compared to that of $z' - K$ versus $J - K$.

3.3 Brightness distribution of a Type 2 LAE

In Fig. 8, the brightness distributions of Ly α emission and those at observed-frame K -band flux (which corresponds to rest-frame 6000 \AA flux) are shown for a Type 1 LAE at $z = 3.1$. The angular resolution (pixel size) is set to be 1 arcsec. The brightness distributions at observed-frame K -band flux trace basically stellar mass distribution. As seen in Fig. 8, both distributions are compact ($\approx 10 h^{-1} \text{ kpc}$), and the extents are quite similar to each other. In Fig. 9, the brightness distributions are shown for a Type 2 LAE at $z = 3.1$. The Ly α emission is diffusely distributed over $\approx 100 h^{-1} \text{ kpc}$ or stronger at the outskirts, while the brightness distributions at observed-frame K -band flux exhibit a strong contrast and are more concentrated. Moreover, Type 2 LAE is composed of some clumps. Such clumpy structures can be seen some observed LABs in the SSA22 region (Uchimoto et al. 2008; Webb et al. 2009). This result suggests that some Type 2 LAEs may not be well dynamically

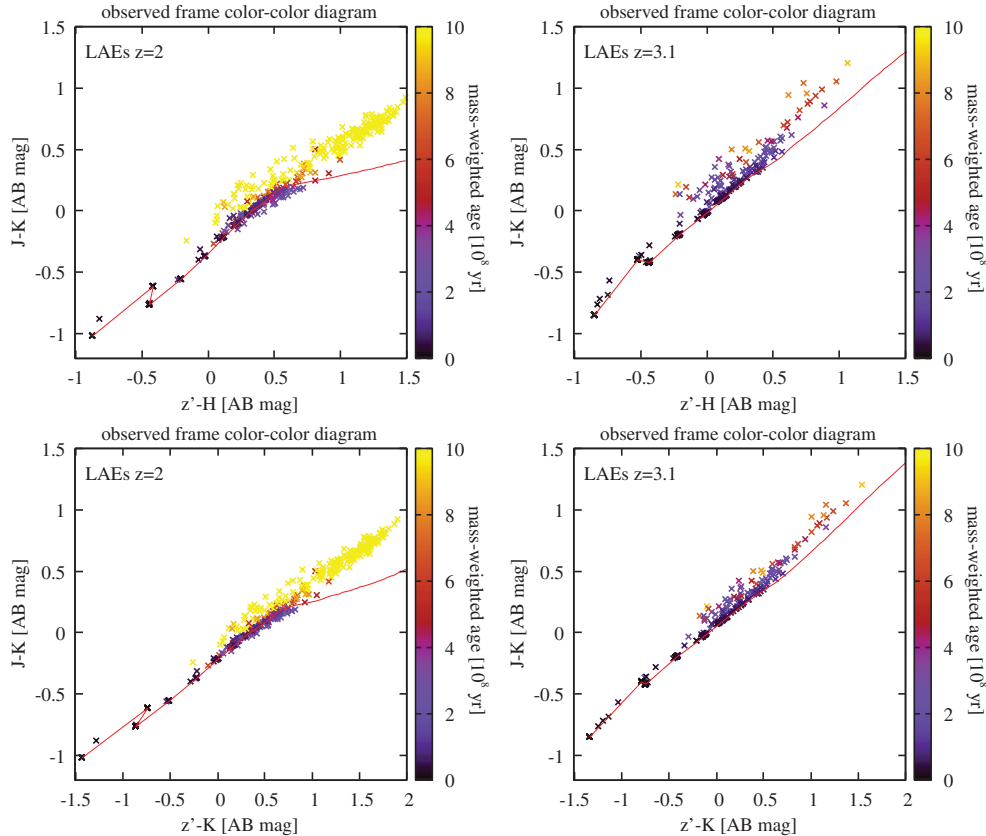


Figure 7. Two-colour diagrams in observed frames. The upper two panels are $z' - H$ versus $J - K$, where the left-hand panel is shown for LAEs at $z = 2$ and the right-hand panel is at $z = 3.1$. The lower two panels are $z' - K$ versus $J - K$, where the left-hand panel is shown for LAEs at $z = 2$ and the right-hand panel is at $z = 3.1$. A red line in each panel denotes the evolutionary track of a single starburst. The mass-weighted ages are shown by colours with an attached colour legend bar.

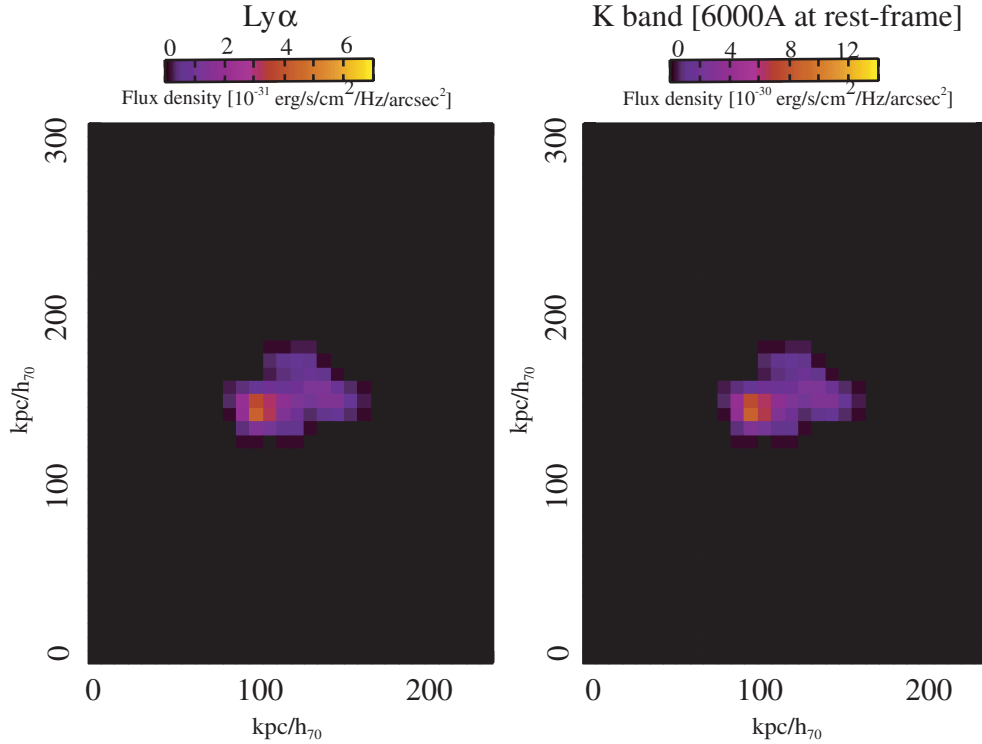
Type 1 LAE at $z=3.1$ 

Figure 8. The brightness distributions of a Type 1 LAE at $z = 3.1$. Left- and right-hand panels show the brightness distributions of $\text{Ly}\alpha$ emission, and those at observed-frame K -band flux (which corresponds to rest-frame 6000\AA flux), of stellar components, respectively. Each colour bar shows the flux of $\text{Ly}\alpha$ emission and observed-frame K -band flux, respectively. The angular resolution (pixel size) is set to be 1 arcsec.

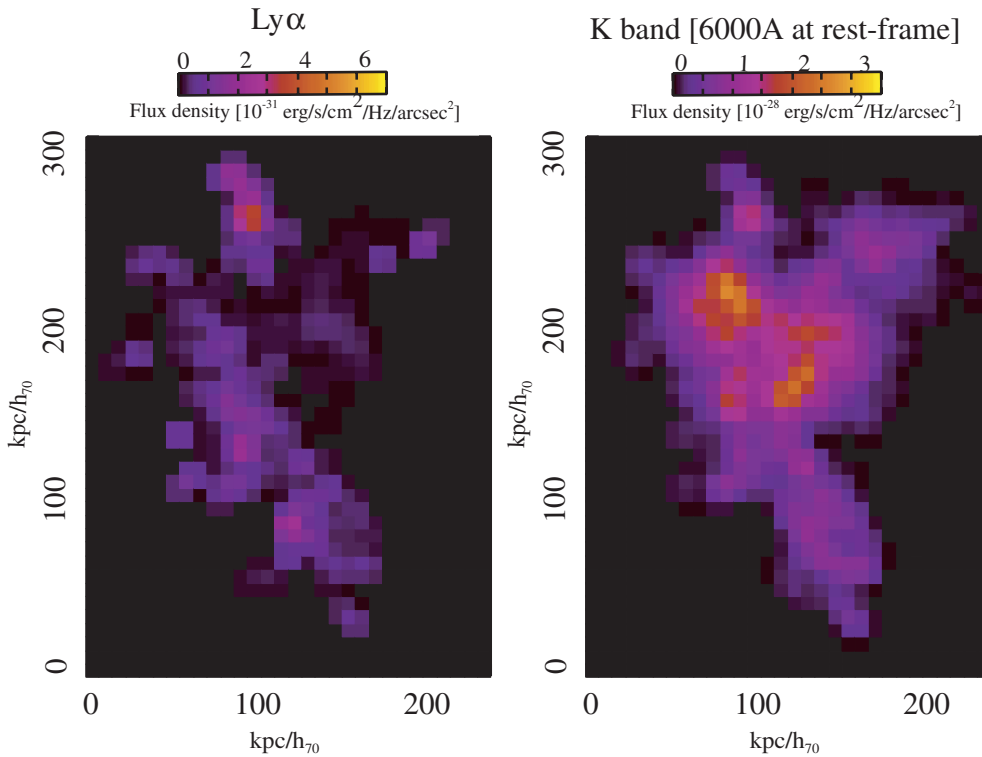
Type 2 LAE at $z=3.1$ 

Figure 9. Same as Fig. 8, but for a Type 2 LAE at $z = 3.1$.

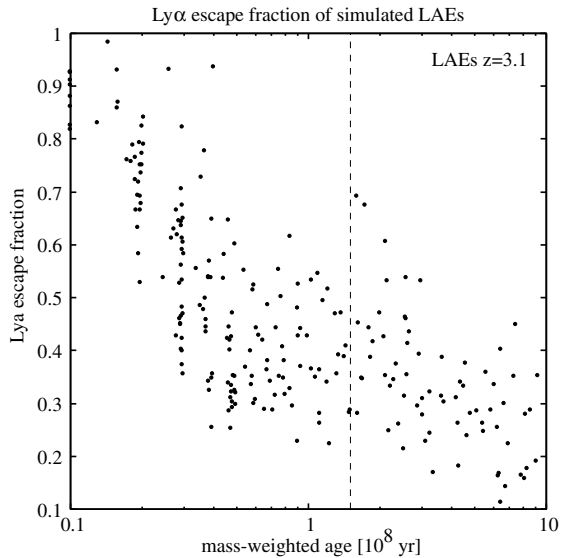


Figure 10. Escape fractions of Ly α photons as a function of mass-weighted ages of LAEs at $z = 3.1$.

relaxed after mergers, since the duration of strong Ly α emission is shorter than the relaxation time of such a large system.

Since Ly α emission is radiated mostly by starbursts, Ly α bright regions correspond to sites of subhalo accretion. These results suggest that if we observe LAEs in various wavelengths, the extent and morphology of Type 2 LAEs appear to be different in each band. Recently, such an offset has been reported in local starburst galaxy (Hayes et al. 2007; Östlin et al. 2009), while no offset is found in LAEs at a higher redshift of $z = 4.4$ (Finkelstein et al. 2008). This can be related to the result that the number of more extended, older Type 2 LAEs increases at lower redshifts, as shown below.

Ly α emissions are affected more severely by dust extinction than continuum radiation. The effect of dust extinction is expected to be stronger for old metal-enriched systems. In Fig. 10, the escape fractions of Ly α photons are plotted against ages of LAEs. The escape fractions are a decreasing function of LAE ages as anticipated. In particular, in Type 2 LAEs, the escape fractions decrease down to ≈ 10 per cent. Thus, for aged Type 2 LAEs, Ly α EWs or luminosities become smaller than expected purely from star formation rate (see Fig. 4). Nevertheless, in the outskirts of halo, starbursts by delayed subhalo accretion take place frequently, where the dust extinction is relatively small. Hence, Ly α emissions can be brighter in the outskirts of halo.

As shown in Fig. 9, the size of Type 2 LAEs can exceed 100 kpc in physical size. This is comparable to the size of Ly α blobs (LABs; Matsuda et al. 2004). Thus, some of Type 2 LAEs with EW $> 100 \text{ \AA}$ may account for a part of observed LABs.

3.4 The halo-size distributions of simulated LAEs

Here, we analyse the halo-size distributions of simulated LAEs. Fig. 11 represents the halo-size distributions of all simulated LAEs as a function of mass weighted age at $z = 2, 3.1$ and 4.5. Here, the radius from the centre of gravity of a halo within which 95 per cent of the total mass is included is defined as the size of a halo. At $z = 4.5$, there are no Type 2 LAEs. At lower redshifts, Type 2 LAEs appear and the number of more extended, older Type 2 LAEs increases with decreasing redshifts. Interestingly, the range of Type 2 LAE size is quite broad. Small Type 2 LAEs with the size of a few tens

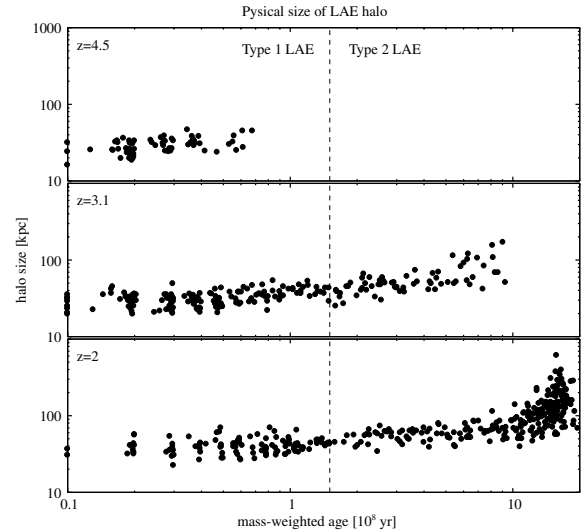


Figure 11. The halo-size distributions of simulated LAEs as a function of mass-weighted age at $z = 2, 3.1$ and 4.5.

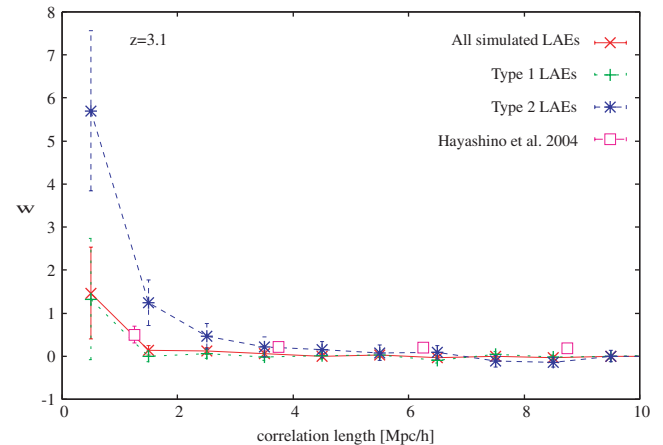


Figure 12. Two-point ACF of all simulated LAEs and each type LAEs at $z = 3.1$. A solid line is ACF of all simulated LAEs, and dashed and dotted lines show ACF of Type 1 and Type 2 LAEs, respectively. Open squares are the ACF of LAEs observed in SSA22a (Hayashino et al. 2004).

kpc are as compact as Type 1 LAEs, while large Type 2 LAEs with the size of a few hundreds kpc are comparable to LABs (Matsuda et al. 2004).

3.5 Clustering properties of two types of LAEs

In order to explore the clustering properties of two types of LAEs, we calculate a two-point angular correlation function (ACF) and a two-point angular cross-correlation function (CCF) between Type 1 and Type 2 LAEs. Fig. 12 represents ACFs of each type LAEs and all simulated LAEs. Furthermore, the ACF of LAEs observed in the SSA22 field (Hayashino et al. 2004) is shown. ACF of Type 1 LAEs as well as ACF of all simulated LAEs is quite weak and well matches the observed ACF in the SSA22 field, whereas ACF of Type 2 LAEs is significantly stronger than that of Type 1 LAEs. This implies that Type 1 LAEs preferentially reside lower density regions at $z = 3.1$, as shown by Shimizu et al. (2007), while Type 2 LAEs are located in higher density regions. The correlation strength of Type 2 LAEs is comparable to that of LBGs in SSA22 region

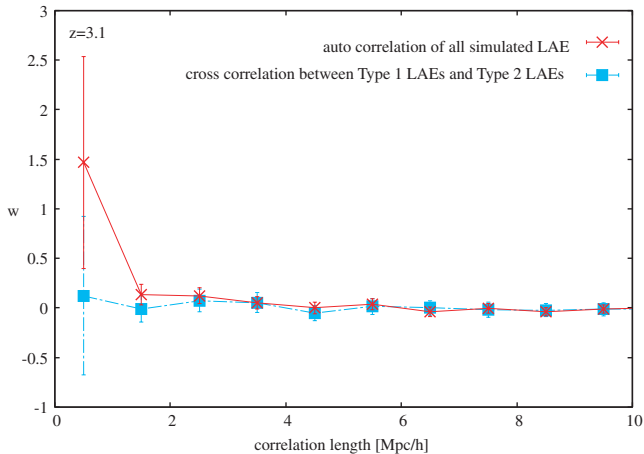


Figure 13. Two-point angular CCF of simulated LAEs. CCF between Type 1 and Type 2 LAEs is depicted by a dash-dot line. For comparison, ACF of all simulated LAEs is also shown by a solid line.

(Giavalisco et al. 1998). This result suggests that Type 2 LAEs may be a subsample of LBGs with strong Ly α emission.

Fig. 13 shows CCF between Type 1 and Type 2 LAEs. The CCF is still weaker than ACF of all simulated LAEs. Very recently, Tamura et al. (2009) have found that the cross-correlation between submm galaxies (SMGs) and LAEs in the SSA22 field is very weak. Type 2 LAEs possess a large amount of dust. If many Type 2 LAEs can be detected as SMGs, our simulation is consistent with this observation.

4 CONCLUSIONS AND DISCUSSION

To explore the origin of two populations of LAEs recently found, we have performed three-dimensional cosmological N -body simulations of subhalo merging history in a Λ CDM universe. We have incorporated star formation history, SED evolution and dust extinction. As a result, we have found that the age of simulated LAEs can spread over a wide range from 2×10^6 to 9×10^8 yr. Furthermore, we have revealed that there are two types of LAEs. We have defined LAEs younger than 1.5×10^8 yr as Type 1s, and older ones as Type 2s. In Type 1 LAEs early coeval starbursts occur in small parent haloes, while in Type 2 LAEs delayed starbursts take place in evolved massive haloes as a consequence of delayed accretion of subhaloes. A parent halo can experience repeatedly a Type 2 LAE phase after a Type 1 LAE phase.

The stellar mass of Type 1 LAEs is $M_{\text{star}} \lesssim 5 \times 10^8 M_{\odot}$, while Type 2 LAEs are as massive as $M_{\text{star}} \sim 5 \times 10^8 - 3 \times 10^{10} M_{\odot}$. The physical properties of Type 1 and Type 2 LAEs are concordant with those of two populations of LAEs observed with multiwavelengths (Finkelstein et al. 2007, 2009a; Matsuda et al. 2007; Lai et al. 2008; Uchimoto et al. 2008). The fraction of Type 2s in all LAEs is a function of redshift, which is less than 2 per cent at $z \gtrsim 4.5$, ~ 30 per cent at redshift $z = 3.1$ and ~ 70 per cent at $z = 2$. This trend is consistent with two populations of LAEs found by Nilsson et al. (2009). Type 2 LAEs are expected to be discriminated clearly from Type 1 LAEs in two-colour diagrams of $z' - H$ versus $J - K$. We find that the brightness distribution of Ly α in Type 2 LAEs is more extended than the main stellar component, in contrast to Type 1 LAEs. This is not only because delayed starbursts tend to occur in the outskirts of a parent galaxy, but also because Ly α photons are effectively absorbed by dust in an evolved galaxy. The

sizes of Type 2 LAEs range from a few tens to a few hundreds kpc. At lower redshifts, the number of more extended, older Type 2 LAEs increases. Small Type 2 LAEs are as compact as Type 1 LAEs, while large Type 2 LAEs exceeding 100 kpc are comparable to LABs (Matsuda et al. 2004).

Moreover, we have found that the clustering of Type 2 LAEs is even stronger than Type 1 LAEs. The amplitude of angular correlation function of Type 2 LAEs is comparable to that of LBGs (Giavalisco et al. 1998). This suggests that LBGs with strong Ly α line can be Type 2 LAEs. The two-point angular cross-correlation function is still weaker than that of all LAEs. If many Type 2 LAEs can be detected as SMGs, this result is consistent with recent observation by Tamura et al. (2009).

Interestingly, in a low-redshift universe at $0.2 < z < 0.35$, the *Galaxy Evolution Explorer* (GALEX) have found many LAEs older than 2×10^8 yr, more massive than $10^9 M_{\odot}$ in stellar component, and having small escape fractions of Ly α photons (Deharveng et al. 2008; Finkelstein et al. 2009b). These properties are quite similar to those of Type 2 LAEs we defined in this paper. Hence, local LAEs could be a good sample to study the detailed physical states of Type 2 LAEs.

Furthermore, in an evolved population of LAEs, active galactic nucleus (AGN) events may be anticipated, since supermassive black holes reside evolved galaxies in a local universe (e.g. Marconi & Hunt 2003, and references therein). Recently, Yamada et al. (2009) have found that AGN are exclusively (90 per cent) associated with the massive objects with stellar mass larger than $10^{10.5} M_{\odot}$. Also, GALEX found that in low-redshift LAEs an AGN fraction is as high as 40 per cent (Finkelstein et al. 2009c). These findings may imply that Type 2 LAEs could have a higher fraction of AGN. Hence, it seems worth investigating the contribution of AGN to Ly α emission especially for Type 2 LAEs (Shimizu & Umemura, in preparation).

ACKNOWLEDGMENTS

We are grateful to T. Hayashino, T. Yamada, Y. Matsuda and R. Yamauchi for providing valuable information and helpful comments, and to M. Mori and R. M. Rich for valuable discussion. Numerical simulations have been performed with computational facilities at Center for Computational Sciences, University of Tsukuba, and the EUP cluster system installed at Graduate School of Frontier Sciences, University of Tokyo. This work was partially supported by the *FIRST* project based on Grants-in-Aid for Specially Promoted Research (16002003) and Grant-in-Aid for Scientific Research (S) (20224002), and also by Grant-in-Aid for Young Scientists (S) (20674003).

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