PROBING THE LONG GAMMA-RAY BURST PROGENITOR BY Lyα EMISSION OF HOST GALAXIES

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ABSTRACT

Long gamma-ray bursts (GRBs) have been suggested to occur preferentially in low-metallicity environment. We discuss the possibility and theoretical aspects of using Lyα emission properties of long GRB host galaxies as a metallicity indicator of high-redshift GRB environments, where direct metallicity measurements are not easy. We propose to use the fraction of Lyα emitters (LAEs) in long GRB host galaxies as a function of UV luminosity, which can be compared with star formation rate weighted LAE fraction of Lyman break galaxies as the standard in the case of no metallicity dependence. There are two important effects of metallicity dependence of long GRB rate to change the LAE fraction of host galaxies. One is the enhancement of intrinsic Lyα equivalent width (EW) by stronger ionizing UV luminosity of low-metallicity stellar population, and the other is extinction by interstellar dust to change the observable EW. Based on a latest theoretical model of LAEs that reproduce observations, we argue that the latter is likely to work in the opposite direction to the former, i.e., to decrease LAE fraction if GRBs preferentially occur in low-metallicity environments, because of the clumpy interstellar medium effect. The high LAE fraction of GRB host galaxies indicated by observations is quantitatively explained by the LAE model if GRBs occur when $Z \lesssim 0.1Z_\odot$, although this result is still indicative because of the limited statistics and theoretical uncertainties. This result demonstrates that the LAE statistics of GRB hosts may give us useful information in the future.

Key words: galaxies: high-redshift – gamma rays: bursts

1. INTRODUCTION

Long gamma-ray bursts (GRBs; hereafter GRB means long gamma-ray burst unless particularly mentioned) are the brightest astronomical transient event, giving us an important laboratory of high-energy astrophysics in extreme conditions, and an important tool to probe the high-redshift universe. Association of some observed GRBs with energetic type Ic supernovae (SNe) is considered to be an observational evidence that GRBs originate from core-collapses (CCs) of very massive stars (e.g., SNe) is considered to be an observational evidence that GRBs originate from core-collapses (CCs) of very massive stars (e.g., MacFadyen & Woosley 1999; Hjorth et al. 2003; Stanek et al. 2003). However, the occurrence rate of GRBs is much lower than that of normal CC SNe, and the condition required for a GRB to occur from a CC still remains as one of the most outstanding questions about GRBs.

Theoretical studies on possible GRB progenitors and production mechanisms of GRBs (e.g., MacFadyen & Woosley 1999; Yoon & Langer 2005; Yoon et al. 2006; Woosley & Herger 2006) suggest that low metallicity may be a necessary condition for the progenitor to produce a GRB event. It has also been suggested from observations that GRB host galaxies are systematically fainter than those in the case that GRBs are unbiased tracer of star formation or CC SN rate, indicating that GRBs may preferentially occur in low-metallicity environment because fainter or smaller galaxies generally have lower metallicity (Le Floc’h et al. 2003; Fruchter et al. 2006; Wolf & Podsiadlowski 2007). These interpretations have also been supported by studies using theoretical models of galaxy formation and evolution (Nuza et al. 2007; Lapi et al. 2008). Furthermore, Stanek et al. (2006) reported that the distribution of metallicity of five GRB host galaxies at $z < 0.25$ is significantly biased toward low metallicity compared with the expectation when GRBs are unbiased star formation tracer.

However, spectroscopic estimates of metallicity are available only for galaxies at low redshifts ($z \lesssim 1$; Stanek et al. 2006; Savaglio et al. 2009), while majority of GRBs occur at higher redshift. At higher redshifts, the metallicity of host galaxies is discussed based on host galaxy luminosity or mass, with the empirical relation of luminosity–metallicity and mass–metallicity ($M–Z$; Fruchter et al. 2006; Chen et al. 2009). However, there is a large scatter in the $L–Z$ relation. Although the $M–Z$ relation of galaxies is tighter than the $L–Z$ relation (Tremonti et al. 2004; Erb et al. 2006), rest-frame infrared luminosity must be measured to reliably estimate galaxy stellar mass, which requires mid-infrared observations such as those by Spitzer. Therefore, it would be useful if there is another and independent metallicity-sensitive property of galaxies that can relatively easily be observed even at high redshifts ($z \gtrsim 1$), where the majority of GRBs occur. In this paper, we consider to use the Lyα emission of galaxies as such an indicator.

Lyman alpha emitters (LAEs) can be detected from very large redshifts by their strong Lyα emission lines (Ouchi et al. 2008; Martin et al. 2008; Sawicki et al. 2008; Finkelstein et al. 2009; Nilsson et al. 2009; Shioya et al. 2009), including the currently highest redshift galaxy confirmed spectroscopically at $z = 6.96$ (Iye et al. 2006, Ota et al. 2008). LAEs (typically defined as galaxies having rest-frame equivalent width (EW) $\gtrsim 20$ Å) are found only in metal poor galaxies in the local universe (Charlot & Fall 1993). Studies of spectral energy distribution (SED) of LAEs at $z \gtrsim 3$ have suggested that they are typically younger and less-massive than UV-continuum selected galaxies (e.g., Lyman break galaxies (LBGs)) at similar redshifts (e.g. Gawiser et al. 2006; Nilsson et al. 2007; Finkelstein et al. 2007; Lai et al. 2008), indicating low metallicity of LAEs. Since low-metallicity stars emit more ionizing UV photons, it is theoretically expected that low-metallicity galaxies tend to have large Lyα EW. Metallicity may affect the Lyα properties also through extinction by interstellar dust (see Section 2.3). Therefore, although some other effects such as dynamics of interstellar medium (ISM) may well play an important role to determine the Lyα properties (Atek et al. 2008, and references therein),
the probability of GRB host galaxies being LAEs could be an indicator of metallicity dependence of GRB rate that can be used even at high redshifts. In fact, observations have indicated that the LAE fraction in GRB host galaxies may significantly be higher than that of field galaxies. Though the sample is still small, almost all of high redshift ($z > 2$) GRB hosts are LAEs (Fynbo et al. 2002, 2003; Jakobsson et al. 2005), while only about 10%–25% of LBGs at similar redshifts have such strong Ly$\alpha$ emission lines (Shapley et al. 2003; Reddy et al. 2008).

We will discuss the theoretical aspects of Ly$\alpha$ emission of GRB host galaxies, and prospect for using it as a tool to get information about GRB progenitor from future observations, especially about the metallicity dependence, based on the latest developments of observations and theoretical models of high-redshift LAEs. Lapi et al. (2008) also discussed LAEs as GRB host galaxies based on the LAE model of Mao et al. (2007), but their model assumes that “intrinsic” ionizing photon luminosity (i.e., that originally from stars without taking into account extinction or absorption) in each galaxy is simply proportional to star formation rate (SFR) in the galaxy, without dependence on age or metallicity. It is difficult to examine the dependence of LAE fraction on metallicity with such a modeling. Here, we use one of the latest models of LAE luminosity functions (LFs) of Kobayashi et al. (2007, 2009, hereafter KTN07 and KTN09). This is based on a hierarchical clustering model of galaxy formation in the framework of cosmological structure formation theory, and the intrinsic ionizing luminosity is calculated using star formation history taking into account metallicity evolution (see Section 2.2), and hence dependence of Ly$\alpha$ luminosity on properties of stellar population can be examined in a realistic way.

In Section 2, we discuss general theoretical aspects of Ly$\alpha$ emission and its dependence on galaxy properties and introduce the LAE model used in this work. In Section 3, we discuss observational strategies to extract useful information about GRB progenitors from future data sets, with least dependence on theoretical uncertainties. In Section 4, we quantitatively investigate how the fraction of LAEs in GRB host galaxies could be affected, if the GRB rate is dependent on metallicity. In Section 5, we compare our model prediction to current observed data set, and also discuss the age effect of the GRB progenitor and the selection effect on host galaxies induced by extinction of GRB optical afterglows. We will summarize our conclusion in Section 6. We assume ΛCDM cosmology with $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and use the AB magnitude system throughout this paper.

2. THEORETICAL BACKGROUND AND THE MODEL OF LAEs

2.1. The Galaxy Formation Model

To construct a mock numerical catalog of galaxies, we utilize one of the latest hierarchical clustering models (so-called semianalytical models) of galaxy formation by Nagashima & Yoshii (2004). This model, which we call the Mitaka model here, produces numerical catalogs of galaxies and their evolution by semianalytic computation of merger history of dark matter (DM) halos and phenomenological model calculation of evolution of baryons. The computation of DM halo merger history is based on the standard theory of structure formation driven by cold DM. The model calculation of baryon evolution within DM halos includes radiative cooling, star formation, SN feedback, and galaxy mergers. Metal enrichment history (chemical evolution) of ISM is calculated self-consistently by the star formation history in each galaxy.

The Mitaka model can reproduce wide variety of observed properties of local galaxies (Nagashima & Yoshii 2004) as well as those of high-redshift LBGs (Kashikawa et al. 2006). In Figure 1, we show cosmic star formation history (CSFH) computed in the Mitaka model with and without metallicity limit. The metallicity-limited CSFHs ($Z < 0.4 Z_\odot$ and $0.2 Z_\odot$) have their peak at higher redshifts than that of total CSFH. The evolution of cosmic SFR and dependence on the metallicity limit are similar to those in other models utilized in studies of GRB rate evolution (e.g., Daigne et al. 2006; Langer & Norman 2006; Lapi et al. 2008), indicating that our model CSFH is broadly consistent with the GRB flux or redshift distributions, within the uncertainties about GRB luminosity function.

2.2. Ly$\alpha$ Photon Production

KTN07 extended this model to describe LAEs. Most of previous studies simply assumed that Ly$\alpha$ luminosity is simply proportional to SFR, but the KTN07 model incorporates the effect of dust extinction with amount different from that for UV continuum, and the effect of outflow. The KTN07 succeeded to reproduce the Ly$\alpha$ LF at various redshifts. Furthermore, KTN09 compared this model comprehensively with various observed data of UV continuum LF and EW distribution of LAEs, and found a good agreement. We use the latest KTN09 model for the analysis in this paper, and see this paper for detailed description of the LAE modeling.

There are several important ingredients to determine the Ly$\alpha$ luminosity from a galaxy. The first is the ionization luminosity ($\lambda < 912$ Å) that is calculated by star formation history and metallicity in each galaxy in the KTN09 model. Then, the model predicts the intrinsic Ly$\alpha$ luminosity assuming that a part of ionizing photons are absorbed within the galaxy and reprocessed into Ly$\alpha$ photons by the case B recombination. The fraction of ionizing photons that are absorbed by neutral hydrogen to produce Ly$\alpha$ is treated as a part of the overall normalization factor of Ly$\alpha$ ($f_\alpha$, see Section 2.3). The “intrinsic” EW is then determined by the ratio of the intrinsic Ly$\alpha$ luminosity to the
UV continuum luminosity. Figure 2 shows the evolution of the intrinsic EW for single burst stellar population or the case of constant SFR for a variety of metallicity, calculated by the model of Schaerer (2003), assuming the Salpeter IMF in the range of 1–100 $M_\odot$. Since stellar populations with low metallicity emit more ionizing photons compared with UV continuum photons around Ly$_\alpha$, EW becomes larger. This effect is significant in young stellar populations ($\lesssim$ several $\times 10^6$ yr). LAEs having such young age estimates have actually been observed (e.g., Chary et al. 2005; Lai et al. 2007), and they are important to reproduce large EW LAEs in the model of KTN09. This is one of the important motivations to consider LAEs as the metallicity indicator of GRB progenitors.

A caveat here is that the stellar evolution theory predicting the ionization luminosity may still be highly uncertain at such young ages, because of e.g., the treatment of the atmosphere of Wolf–Rayet stars (García-Vargas et al. 1995) and stellar rotation (Vázquez et al. 2007). Our model is based on the widely used model of Schaerer (2003), and qualitative trend that younger and lower metallicity stellar population should have large intrinsic Ly$_\alpha$ EW is generally accepted.

2.3. Ly$_\alpha$ Escape Fraction and Extinction Effect

The observable Ly$_\alpha$ luminosity is determined by the intrinsic luminosity and the escape fraction of Ly$_\alpha$ photons from the galaxy, and KTN09 considered the effects of extinction by dust. KTN09 found that the extinction effect is especially important to successfully reproduce various observations of LAEs. In KTN09 model, the Ly$_\alpha$ luminosity of a galaxy including the extinction effect is computed as

$$L_{\text{Ly}\alpha} = f_0 \frac{1 - \exp(-\tau_{\text{Ly}\alpha})}{\tau_{\text{Ly}\alpha}} L_{\text{Ly}\alpha}^{\text{max}},$$

where $\tau_{\text{Ly}\alpha}$ is an optical depth of the galaxy for Ly$_\alpha$ photons, and $L_{\text{Ly}\alpha}^{\text{max}}$ is Ly$_\alpha$ emitted in the galaxy if all ionizing photons are reprocessed into Ly$_\alpha$ photons. The parameter $\tau_{\text{Ly}\alpha}$ is proportional to that of UV continuum, $\tau_{\text{UV}}$, and both scales with the metal column density of galaxies calculated in the Mitaka model. The overall normalization factor ($f_0$) and normalization of $\tau_{\text{Ly}\alpha}$ are determined by fitting to the observed LAE Ly$_\alpha$ luminosity functions.

Because of the resonant scattering by neutral hydrogens, Ly$_\alpha$ photons would take vastly different paths in a galaxy from those of UV continuum photons, and hence $\tau_{\text{Ly}\alpha}$ can be very different from $\tau_{\text{UV}}$. It is theoretically highly uncertain whether this effect reduces or enhances Ly$_\alpha$ EW, and there are two extreme possibilities: extinction of Ly$_\alpha$ photons can be much more significant (in the case of homogeneous ISM, Ferland & Netzer 1979) or much less (in the case of clumpy ISM, Neufeld 1991; Hansen & Oh 2006) than that of UV continuum. Recent observations by Finkelstein et al. (2007, 2008, 2009) have indicated that the clumpy ISM effect is in fact working in high-z LAEs. This has theoretically been supported by KTN09 who independently found that the clumpy ISM case (i.e., $\tau_{\text{Ly}\alpha} \lesssim \tau_{\text{UV}}$) is favored to reproduce the existence of large EW ($>240$ Å) LAEs, EW-reddening correlation, and EW–$L_{\text{UV}}$ correlation. If this interpretation is correct, we expect that galaxies with large metallicity (and hence a large amount of dust) tend to have larger Ly$_\alpha$ EW, which is in the inverse direction to the effect of ionization luminosity mentioned above.

It has been argued that LAEs are less dusty galaxies, both theoretically (e.g., Ferland & Netzer 1979) and observationally (Gawiser et al. 2006, 2007; Gronwall et al. 2007; Nilsson et al. 2007; Lai et al. 2008; Ouchi et al. 2008). These claims appear in contradiction with the preference of the clumpy ISM dust suggested by recent studies of Finkelstein et al. (2007, 2008, 2009) and KTN09. However, this can be understood by Figure 7 of KTN09 where the plot of extinction ($A_{1500}$ at 1500 Å) versus EW is shown for the model and the observed data. If one selects LAEs with modest values of EW ($\lesssim 100$ Å), the extinction is relatively small, while the observed data of Finkelstein et al. (2009) indicate that LAEs with large EW ($\gtrsim 100$ Å) are more dusty, which is also reproduced by the KTN09 model. Since LAEs with EW $\lesssim 100$ Å are more abundant, a conclusion that LAEs are not dusty could be derived depending on the sample size and selection criteria of LAEs.

2.4. Remarks about LAE Theory in the Context of This Work

As discussed above, the consequence of the metallicity dependence of GRBs on the Ly$_\alpha$ properties of host galaxies would be rather complicated and theoretically still uncertain. We use the KTN09 as the guideline in this work, but it should be noted that there are still large uncertainties in understanding of LAEs. Some of the theoretical predictions may be for particular cases, or be changed by future studies. However, our result would still be useful as the first step to consider future possible use of LAEs to derive some information about GRBs. We also emphasize that the KTN09 model is one of the latest ones, and unique to reproduce observed data consistently at various redshifts for all of the LAE LF in Ly$_\alpha$ and UV continuum luminosities, EW distributions, and $L_{\text{Ly}\alpha}$ versus EW correlations, taking into account the selection criteria of LAEs in each observation.

3. OBSERVATIONAL STRATEGY

It is not straightforward to extract useful information from the statistics of LAE fraction in GRB host galaxies. Even if GRBs are simply tracing SFR, the LAE fraction for a given sample of GRB host galaxies is weighted by SFR of galaxies, and hence different from that for a sample of galaxies found by flux-limited...
galaxies than the simple number fraction of LAEs in galaxy trace SFR, we still expect a higher LAE fraction of GRB host there is no metallicity effect about GRB rates, and GRBs simply do not simply follow SFR in galaxies. A caveat is possible selection effects in detecting GRB host galaxies. If the detection efficiency of GRB hosts does not depend on galactic properties except for the flux limit for galaxies, the comparison will not be biased. However, even if the prompt and afterglow emission properties do not depend on host properties, the detection probability of optical afterglow could be affected by extinction in galaxies. We will discuss this issue later in this paper (Section 5.3).

We need estimates of SFR of galaxies in the galaxy survey sample. One possibility is to use rest-frame UV luminosity as the SFR indicator, because this is always available for galaxies found by the Lyman-break method (i.e., LBGs). However, UV luminosity may be affected by extinction, and a more reliable SFR estimate is favorable. Such an estimate is also possible, e.g., by SED fittings to multi-band photometric data or spectroscopic observations (e.g., Shapley et al. 2005). The number of galaxy data sets with such rich information is increasing thanks to the recent developments of high-redshift galaxy searches. It should be noted that an observational SFR estimate is generally an average of SFR until the time of the observation on a timescale that is dependent on SFR indicators. Here, we implicitly assumed that the evolutionary timescale of SFR of a galaxy is longer than the timescale of SFR indicator, so that the SFR estimate is not biased by star formation history. This issue will be discussed in Section 5.2.

The upper panel of Figure 3 shows the simple LAE fraction in number and SFR-weighted LAE fraction of galaxies in the Mitaka model at \( z = 3 \), as a function of restframe UV (\( \lambda = 1500 \) Å) magnitude, \( M_{\text{UV}} \). Two different threshold values of Ly\( \alpha \) EW are adopted as the definition of LAEs. It can be seen that the SFR-weighted LAE fraction is significantly higher than the simple number fraction at a fixed value of \( M_{\text{UV}} \). This can be understood by the effect of clumpy dust for the extinction of Ly\( \alpha \) photons. For a fixed \( M_{\text{UV}} \), galaxies with large extinction should have larger (extinction-corrected) SFR, and large extinction increases Ly\( \alpha \) EW by the clumpy dust effect. Therefore, even if there is no metallicity effect about GRB rates, and GRBs simply trace SFR, we still expect a higher LAE fraction of GRB host galaxies than the simple number fraction of LAEs in galaxy surveys. This result also implies that we should not use simply \( M_{\text{UV}} \) as SFR indicator; if \( M_{\text{UV}} \) is a good SFR indicator, we expect the same value for the SFR-weighted and simple number fractions at a fixed \( M_{\text{UV}} \).

The lower panel of Figure 3 shows the UV continuum LF of galaxies in the Mitaka model. The UV-luminosity-weighted LF and SFR-weighted LF are also shown. The luminosity distribution of GRB host galaxies should be the same as the SFR-weighted LF if GRBs simply trace SFR. The SFR-weighted LF shows some deficit in the largest UV luminosity range, compared with the UV-weighted LF. This can be understood by the fact that galaxies with large extinction tend to have smaller observed (i.e., extinction-uncorrected) UV luminosity, and hence higher SFR compared with UV luminosity. A comprehensive comparison between the model prediction of UV continuum LF in the Mitaka model with observations are presented in KTN09.

4. LOW-METALLICITY PREFERENCE OF GRBS AND LAE FRACTION

Now we consider the effect of the metallicity dependence of GRBs on LAE fraction. As the first simple model, We assume that GRBs occur with a rate proportional to SFR but only when the ISM metallicity of the galaxy is smaller than a critical value, and GRBs do not occur otherwise (the step function model):

\[
R_{\text{GRB}} \propto \begin{cases} \text{SFR}, & Z < Z_{\text{crit}} \\ 0, & Z \geq Z_{\text{crit}} \end{cases}
\]

This simple model of GRB rate was tested in number of studies and reproduced various statistical properties of GRBs such as redshift distribution and \( \log N - \log P \) plot within the range of uncertainty when it is combined with realistic model of star formation history and metallicity of galaxies (e.g., Lapi et al. 2008).

Our interest is in the fraction of LAEs in GRB host galaxies, and hence we do not need to consider the normalization
(the proportionality constant) of $R_{\text{GRB}}$, luminosity function or spectrum of GRB prompt emission. Here, we calculate SFR by that of the model galaxy at the time of an observation, and implicitly assume that the SFR evolution timescale is longer than the typical age of the GRB progenitor. If SFR is changing with a shorter timescale than the progenitor age, the real GRB rate could be different from that calculated by this formulation. This issue will be discussed in Section 5.2.

We then calculate the fraction of LAEs in GRB host galaxies with various values of $Z_{\text{crit}}$ using the Mitaka model at $z = 3$, and the result is shown in Figure 4 as a function of UV luminosity, for the two different threshold values of LAE EW as in Figure 3. The LAE fraction without the metallicity dependence ($Z_{\text{crit}} = \infty$) is plotted together. Compared with the case of no metallicity dependence, the predicted LAE fraction becomes higher at large UV luminosity ($M_{\text{UV}} \lesssim -19$) and lower at faint ($M_{\text{UV}} \gtrsim -19$). These trends can be understood as follows.

Galaxies with relatively small amount of extinction are dominant in the large UV luminosity range, since large extinction would significantly reduce the UV luminosity. In such a regime, the effect of extinction by clumpy ISM on Ly$\alpha$ EWs is not significant, and EWs are mainly determined by stellar population, i.e., larger EWs for younger and lower metallicity galaxies. Therefore, if GRBs trace low metallicity stellar populations, an enhancement of Ly$\alpha$ EW is expected. On the other hand, significantly extincted galaxies populate the low UV luminosity range, and the effect of clumpy ISM dust on Ly$\alpha$ EW is important. The dust/gas ratio should be larger for large metallicity galaxies, and hence our model predicts large Ly$\alpha$ EW for metal-rich galaxies in this regime.

Therefore, the key is that UV-faint galaxies have larger extinction on average, combined with the clumpy ISM effect. This may sound strange for the reader, because it is known that galaxies with larger stellar mass tend to have larger extinction. However, we emphasize that the UV luminosity discussed here is the apparent luminosity that is not corrected for dust extinction. Galaxies with larger stellar mass does not necessarily have larger UV luminosity, due to the larger dust extinction in UV bands. To summarize, the two competing effects of metallicity on the LAE fraction discussed in Section 2, i.e., stellar population and extinction, appear in different ranges of UV luminosity of host galaxies.

We also calculate the LAE fraction of GRB host galaxies integrated by UV magnitude in the range corresponding to the observed data with the threshold EW of 10 Å, and show in the left panel of Figure 5 as a function of the critical metallicity. The LAE fraction rapidly increase with decreasing $Z_{\text{crit}}$ at $Z_{\text{crit}} \sim 0.1 Z_{\odot}$. This metallicity scale is interestingly similar to those suggested by theoretical studies of stellar evolution (Woosley & Herger 2006; Yoon & Langer 2005) and spectroscopically measured metallicity of local GRB host galaxies (Stanek et al. 2006; Savaglio et al. 2009). This sensitivity of the LAE fraction for the metallicity scale of our concern indicates an interesting opportunity to constrain the GRB progenitor by future observations of high-redshift galaxies and GRBs.

It should be noted that the behavior of LAE fraction as a function of $Z_{\text{crit}}$ is not simple, but it depends on the EW threshold and UV magnitude range of the galaxy sample constructed. As discussed previously in this section, LAE fraction increases with decreasing $Z_{\text{crit}}$ in the bright UV magnitude range, and decreases in the faint UV range. Hence, if we consider only brightest galaxies, the LAE fraction converges to unity due to the stellar population effect, which is the case of the left panel of Figure 5. (The effect of clumpy ISM which is into the opposite direction to the ionization luminosity effect is also seen in the range of $Z_{\text{crit}} \sim -0.6 \text{--} -0.3$.) However, if we take fainter UV magnitude range into account, the behavior of LAE fraction becomes complicated. LAE fraction increases with decreasing $Z_{\text{crit}}$ at large $Z_{\text{crit}}$, but the trend turns over and it decreases with decreasing $Z_{\text{crit}}$ at small $Z_{\text{crit}}$, for some values of the EW threshold, as shown in the right panel of Figure 5. This point should be kept in mind when the future observations are used to constrain the nature of the GRB progenitor.

The step function with the critical value of $Z_{\text{crit}}$ is likely to be too simple to describe the realistic GRB production efficiency as a function of metallicity. Therefore, we also try a more smoothly varying function (the Gaussian model):

$$R_{\text{GRB}} \propto \exp\left(-\frac{Z^2}{2\sigma^2}\right) \times \text{SFR},$$

Figure 4. LAE fraction in GRB host galaxies as a function of rest-frame UV ($\lambda = 1500$ Å) magnitude of galaxies predicted by the KTN09 model at $z = 3$, for various values of critical metallicity $Z_{\text{crit}}$ (GRB occurs only when $Z < Z_{\text{crit}}$). The left and right panels are for the different threshold values of EW$_{\text{Ly} \alpha}$ for the LAE definition. Solid line is the case of no metallicity dependence, which is identical to the solid curves of the upper panel of Figure 3. The 68% C.L. confidence region from the observed data in Table 1 is shown by gray scale.

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3 The amount of interstellar dust is assumed to be proportional to the gas metallicity in the Mitaka model.
and the LAE fraction with this model is plotted against $\sigma_Z$ instead of $Z_{\text{crit}}$ in Figure 5. Qualitative result is not changed from the case of the step function model.

5. DISCUSSION

5.1. Comparison to Observations

Here, we compare our result with observations. Currently only one published result is available for the LAE statistics of GRB host galaxies (Jakobsson et al. 2005), which is based on seven GRB hosts with Ly$\alpha$ observations including those of Fynbo et al. (2002, 2003). Their result is summarized in Table 1. In these seven host galaxies, five have strong Ly$\alpha$ emission (EW $> 10$ Å). Though Ly$\alpha$ emissions were not detected in two host galaxies (000301c and 020124), the upper limits are not severe and we cannot exclude the possibility that these two are also LAEs having EW $> 10$ Å. It is difficult to set strong constraints on Ly$\alpha$ EW for galaxies fainter than $\sim 28$ mag in optical (rest UV) bands by the current observing facilities, and hence we do not include the three faintest host galaxies in Table 1 (000301c, 020124 and 030323) in the following discussion.

Now we have four GRB host galaxies at $z \sim 2$–3 with known Ly$\alpha$ EWs of 14–71 Å. Absolute rest UV magnitudes of these are $M_{\text{UV}} \sim -22$–21. It is obvious that the statistics is not yet sufficient, but here we compare these results with our model at $z = 3$ as the first trial.

The observational constraints are indicated by shaded regions in Figure 4, using the confidence limits for small number statistics given by Gehrels (1986). In these plots adopting EW thresholds of 40 and 120 Å, our model predictions are roughly consistent with the observed data, giving no constraint on $Z_{\text{crit}}$. However, if we take the EW threshold of 10 Å and the threshold absolute rest UV magnitude of $M_{\text{UV}} = -5 \log h < -21$ to match the sample of Jakobsson et al. (2005), $Z_{\text{crit}} \lesssim 0.1 Z_\odot$ seems to be favored in our model (Figure 5), which is interestingly consistent with other theoretical or observational indications. However, the statistics is obviously not sufficient, and we need to await future observations to derive more reliable conclusions.

5.2. Progenitor Age Effect on LAE Fraction

As mentioned before, we have implicitly assumed that the evolutionary timescale of SFR in galaxies is longer than the age of the GRB progenitor and the age of stellar population used to observationally estimate SFR. However, if SFR is rapidly changing with a comparable or shorter timescales than these, our argument above could be affected. Since we expect strong Ly$\alpha$ emission from very young stellar population having large ionizing luminosity (Figure 2), the evolutionary time scale of such galaxies might become as short as the time scales of the GRB progenitor or SFR indicators.

| GRB    | Redshift | Host (mag) | $F_{\text{Ly}\alpha}$ (erg s$^{-1}$ cm$^{-2}$) | $L_{\text{Ly}\alpha}$ (erg s$^{-1}$) | Ly$\alpha$ EW$_{\text{rest}}$(Å) |
|--------|----------|------------|---------------------------------------------|-----------------------------------|----------------------------------|
| 971214 | 3.42     | $R = 26.5$ | $4.5 \times 10^{-17}$                       | $5.0 \times 10^{42}$               | $14$                             |
| 000301c| 2.04     | $R = 28.0$ | $2.2 \times 10^{-17}$                       | $1.1 \times 10^{42}$               | $< 150$                         |
| 000926 | 2.04     | $U = 24.9$ | $1.6 \times 10^{-16}$                       | $5.1 \times 10^{42}$               | $71$                            |
| 011211 | 2.14     | $R = 24.9$ | $2.8 \times 10^{-17}$                       | $1.0 \times 10^{42}$               | $21$                            |
| 020124 | 3.20     | $V = 29.3$ | $1.5 \times 10^{-17}$                       | $1.4 \times 10^{42}$               | $< 22$                          |
| 021004 | 2.34     | $R = 24.4$ | $2.5 \times 10^{-16}$                       | $1.1 \times 10^{43}$               | $68$                            |
| 030323 | 2.14     | $V = 28.0$ | $1.2 \times 10^{-17}$                       | $1.3 \times 10^{42}$               | $145$                           |

Notes. Host magnitude of GRB 020124 is from Bloom et al. (2002), and other values are from Jakobsson et al. (2005, see their Table 4, and references therein). The magnitudes have been converted to AB magnitudes.
Figure 6 of KTN09 shows the distribution of mean stellar ages of LAEs in the Mitaka model, where the age is calculated by star formation history of each galaxy with a weight by ionization luminosity. Since ionization luminosity comes from massive stars having short lifetimes, the ionization-luminosity-weighted age is about $10^{6.6}$ yr for stellar population having a constant SFR with a duration much longer this time scale. According to Figure 6 of KTN09, LAEs with large EW have significantly shorter age than this, indicating that their SFR is not constant on this time scale.

If the GRB progenitors have a longer time scale to evolve into a GRB than this scale, the age effect is not negligible. According to the main-sequence lifetimes of massive stars (Schaller et al. 1992; Lejeune & Schaerer 2001), it may be the case. In galaxies whose mean stellar age is significantly shorter than the age of GRB progenitor, we expect a smaller GRB rate than simply expected from SFR because the progenitors do not have enough time to produce GRBs, while such young galaxies have a high probability of being LAEs. This effect would then lead to apparent decrease of LAE fraction of GRB host galaxies, and hence it might be confused with the effect of the low metallicity preference of GRBs combined with the extinction by dust in the clumpy ISM. This is an interesting possibility, and should be kept in mind when we analyze future data sets of GRB host galaxies, though a quantitative prediction is beyond the scope of this work.

The typical lifetime of stars contributing to the continuum UV luminosity at 1500–2800 Å, which is a popularly used SFR indicator, is $\sim$20 Myr (corresponding to $\sim 10 M_\odot$ stars, Madau et al. 1998). Therefore, it is also possible that SFR of LAEs is changing with a time scale shorter than the time scale of the SFR indicator. One must be careful about this when the SFR-weighted LAE fraction of field galaxies is calculated as the reference value corresponding to the case of the SFR-tracing GRB rate.

5.3. Dust Extinction of Optical Afterglows

In most cases, detection of an optical afterglow is required to identify the host galaxy of a GRB at high redshift, and hence a sample of identified GRB host galaxies may be biased against dusty host galaxies in which afterglow light is significantly attenuated. Since the extinction should have a significant effect on the Ly$\alpha$ EW of host galaxies as discussed in Section 2, the extinction bias of GRB host galaxies could affect the LAE statistics of them.

To investigate this effect, we employ a simple method similar to that used to investigate the low metallicity preference of GRB events. We assume that we can identify the host galaxy of a GRB only when the extinction of the galaxy is less than a critical value, and hence the effective GRB rate becomes

$$R_{\text{GRB}} \propto \begin{cases} \text{SFR}, & A_V < A_V^{\text{crit}} \\ 0, & A_V \geq A_V^{\text{crit}} \end{cases} .$$

The LAE fraction of GRB host galaxies at $z = 3$ predicted by this model is shown in Figure 6, and the LAE fraction decreases as the afterglow extinction effect becomes strong (smaller $A_V^{\text{crit}}$). This is simply a manifestation of the effect of extinction by clumpy ISM dust on LAEs, i.e., enhancement of LAE EW by extinction, which is assumed in the model of KTN09. The change of the LAE fraction is into the same direction in all the magnitude range, and it can in principle be distinguishable from the effect of low-metallicity preference of GRBs showing increase and decrease of the LAE fraction with decreasing $Z^{\text{crit}}$ at $M_{\text{UV}} - 5 \log h \lesssim -19$ and $\gtrsim -19$, respectively (Figure 4).

Fynbo et al. (2003) pointed out that the bias against dusty galaxies by the extinction of optical afterglows may be the reason of the observed high-LAE fraction of GRB host galaxies, because it has often been argued that LAEs are less dusty galaxies. However, as discussed in Section 2, recent studies have suggested that the effect of extinction on LAE EW is rather inverse and to increase EW by extinction in clumpy ISM. Therefore, if the indication of the clumpy ISM extinction is correct, the extinction of GRB afterglows is unlikely to cause large LAE fraction among host galaxies.

6. CONCLUSIONS

We discussed the theoretical aspects of using Ly$\alpha$ emission properties of GRB host galaxies to get implications for the GRB progenitor. The fraction of LAEs in a sample of GRB host galaxies can be compared with the SFR-weighted LAE fraction of a sample of LBGs at similar redshift with a similar magnitude limit, and a significant difference, if observed, would
indicate that GRBs do not simply follow SFR and a new physical parameter, such as metallicity, is hidden in the relation between GRB rate and SFR.

To make quantitative predictions we used one of the latest theoretical model of LAEs in the framework of hierarchical galaxy formation, which is successful to reproduce a variety of recent observed data about LAE statistics. We then tested the case that GRBs have preference to low metallicity environments. We found that there are two effects of the metallicity dependence on the LAE fraction of host galaxies. One is the intrinsic EW enhancement by low metallicity; low-metallicity stellar populations have larger ionizing UV luminosity and hence larger Lyα EWs. The other is the extinction by ISM dust; low-metallicity galaxies are expected to be less dusty and dust affects LAE EWs. According to the KTN09 model as well as recent observations, Lyα EWs may be enhanced because of extinction by dust in clumpy ISM. Therefore, the low-metallicity preference of GRBs would decrease the LAE fraction of extinction by dust in clumpy ISM. The observational indication of higher LAE fraction for GRB host galaxies reported by Fynbo et al. (2002, 2003) and Jakobsson et al. (2005) can be explained by our model by the intrinsic EW enhancement effect, if GRBs occur only in low metallicity environment of \( Z \lesssim Z_{\text{crit}} = 0.1 Z_\odot \). However, the statistics is still poor and further systematic observations of GRB host galaxies are highly desired.

We have also discussed the selection effect of GRB host galaxies by extinction of GRB afterglow flux, which is another possible explanation of large LAE fraction. However, recent observations and theoretical modeling indicate that the effect of extinction is to enhance Lyα EW by clumpy ISM, and in this case the selection effect will decrease the LAE fraction.

It should be noted that the theory of LAEs is still highly uncertain, and the quantitative predictions by the KTN09 model suffers from such uncertainties. However, the quantitative behaviors about LAE emission of GRB hosts presented here based on one of the latest models of LAEs would be useful to start consideration about using LAEs to derive information about GRBs by the future data set. Observations of high redshift LAEs are rapidly developing, and near-future observations of LAEs will provide us with further knowledge about this galaxy population. We tried to outline the important theoretical effects and aspects that should be considered when one uses Lyα properties of GRB host galaxies to get any implications about GRBs from future observations.

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