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# THE REIONIZATION HISTORY AND EARLY METAL ENRICHMENT INFERRED FROM THE GAMMA-RAY BURST RATE

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## ABSTRACT

Based on the gamma-ray burst event rate at redshifts of $4 \leq z \leq 12$, which is assessed by the spectral peak energy-to-luminosity relation recently found by Yonetoku et al., we observationally derive the star formation rate (SFR) for Population III (Pop. III) stars in a high-redshift universe. As a result, we find that Pop. III stars could form continuously at $4 \leq z \leq 12$. Using the derived Pop. III SFR, we attempt to estimate the ultraviolet (UV) photon emission rate at $7 \leq z \leq 12$ in which redshift range no observational information has been hitherto obtained on ionizing radiation intensity. We find that the UV emissivity at $7 \leq z \leq 12$ can make a noticeable contribution to the early reionization. The maximal emissivity is higher than the level required to keep ionizing the intergalactic matter (IGM) at $7 \leq z \leq 12$. However, if the escape fraction of ionizing photons from Pop. III objects is smaller than 10%, then the IGM can be neutralized at some redshift, which may lead to the double reionization. As for the enrichment, the ejection of all metals synthesized in Pop. III objects is marginally consistent with the IGM metallicity, although the confinement of metals in Pop. III objects can reduce the enrichment significantly.

*Subject headings:* early universe — gamma rays: bursts — stars: formation

## 1. INTRODUCTION

The recent observation of the cosmic microwave background by the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) has revealed that the dark age in the universe ended quite early by the reionization at $z_r \sim 20^{+10}_{-9}$ (Bennett et al. 2003; Spergel et al. 2003) but that the origin of ionizing radiation in such an early epoch and the subsequent ionization history after the early reionization are not elucidated very well. The first possibility for the ionizing source is Population III (Pop. III) stars (Cen 2003a; Ciardi et al. 2003; Wyithe & Loeb 2003; Somerville & Livio 2003; Fukugita & Kawasaki 2003), and the other possibilities are miniquasars (Madau et al. 2004) or black hole accretion (Sasaki & Umemura 1996; Ricotti & Ostriker 2004b). The early reionization by Pop. III stars has recently been under debate. Sokasian et al. (2004) argue that the reionization by Pop. III stars is marginally compatible with the Thomson optical depth measured by the *WMAP*, $\tau_e = 0.17 \pm 0.04$, even if the escape fraction of ionizing photons from early formed objects is unity. In addition, Ricotti & Ostriker (2004a) explore the feedback effect by supernova (SN) energy input in Pop. III objects and find that the suppression of Pop. III star formation by SNe is so intensive that Pop. III stars cannot contribute significantly to the cosmic reionization. The strong suppression of Pop. III star formation or the early shift to Pop. II or Pop. I star formation may bring the vanishment of ionizing radiation, resulting in the re-neutralization of the intergalactic medium (IGM). This may lead to the so-called double reionization (Cen 2003b; Wyithe & Loeb 2004).

Also, Pop. III SNe can be the origin of IGM heavy elements (Nakamura & Umemura 2001; Scannapieco et al. 2002; Ricotti & Ostriker 2004a). The detailed analysis of quasar metal absorption lines have shown that the IGM is enriched by heavy elements from a level of $\sim 10^{-3}\ Z_\odot$ at $z \lesssim 4.3$ to $\sim 10^{-4}\ Z_\odot$ at $z \sim 5.3$, where $Z_\odot$ is the solar abundance (Cowie & Songaila 1998; Songaila 2001). It is quite perplexing that heavy elements are observed commonly and uniformly in the low-density space where no bright galaxies are found. Although the outflow from small protogalaxies could be responsible for the enrichment of the IGM (Madau et al. 2001; Mori et al. 2002), the much earlier enrichment by Pop. III objects may provide a potential solution for the uniformly distributed metagalactic heavy elements. Hence, Pop. III star formation history in high redshifts could be a key to the early enrichment.

We cannot observe directly Pop. III stars at $7 < z < z_r$, but gamma-ray bursts (GRBs) at high redshifts can be a potential tool to probe the formation history of Pop. III stars. Since the discovery of X-ray afterglow from GRB 970228 (Costa et al. 1997; van Paradijs et al. 1997), the distances to bright GRBs are known to be cosmological (Metzger et al. 1997). The most distant GRB hitherto identified spectroscopically is GRB 000131 at $z = 4.5$ (Andersen et al. 2000).[3] However, there are numerous much weaker GRBs without known distance, listed in the archive of the Burst and Transient Source Experiment (BATSE) on board the *Compton Gamma Ray Observatory*.[4] Recently, Yonetoku et al. (2004) estimated distances of 689 BATSE weak GRBs, based on the spectral peak energy-to-

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[3] See table of GRB distances by J. Greiner at http://www.mpe.mpg.de/~jcg/grb.html.
[4] See database archive at http://www.batse.msfc.nasa.gov.

luminosity relation (Amati et al. 2002; Yonetoku et al. 2004), and found that most of the GRBs are more remote up to $z \sim 12$. A recent great advance in our understanding of GRBs is the finding of the obvious association between GRB 030329 and SN 2003dh (Hjorth et al. 2003; Greiner et al. 2003; Matheson et al. 2003; Price et al. 2003; Uemura et al. 2003). This association firmly established the connection between a GRB and an energetic supernova (hypernova), which is the collapse of a massive star (Woosley et al. 1999; Paczyński 1998). Since Pop. III stars are likely to form in a top-heavy initial mass function (IMF; Bromm et al. 1999; Abel et al. 2000, 2002; Nakamura & Umemura 2001), a portion of GRBs at high redshifts possibly result from Pop. III hypernovae. Actually, Heger et al. (2003) estimated the fraction of Pop. III GRBs using the IMF by Nakamura & Umemura and found that several percent of Pop. III stars result in GRBs.

In this Letter, we derive the star formation rate (SFR) of Pop. III stars observationally for the first time out to $z \sim 12$ by the use of the absolute GRB event rate. Then, using the Pop. III SFR, we assess the UV photon emission rate at $7 \leq z \leq 12$, in which redshift range no observational constraint has been hitherto placed on ionizing radiation intensity. Also, we analyze the early metal enrichment of the IGM by the derived Pop. III SFR. Here, we assume a ΛCDM universe with $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, and $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$ (Bennett et al. 2003; Spergel et al. 2003).

## 2. GRB RATE AND POP. III SFR

### 2.1. *Absolute GRB Event Rate*

Yonetoku et al. (2004) published the relative value of the GRB event rate up to $z \sim 12$, based on the spectral peak energy-to-peak luminosity relation. In this Letter, we need to estimate an absolute value of the GRB event rate ($\dot{\rho}_{\rm GRB}$) in the early universe. In order to do that, it is necessary to make corrections for jet collimation, because the GRB emission is collimated in the order of 0.1 radians (Kulkarni et al. 1999; Frail et al. 2001). If the reported evolution in luminosity (Yonetoku et al. 2004) can be attributed to the evolution of jet collimation, we can correct the collimation using the observed evolution in luminosity with the index $\kappa$ defined as $(1+z)^{2.6\kappa}$, where 2.6 represents the observed evolution in luminosity (Yonetoku et al. 2004). After the correction for jet collimation, the absolute event rate $\dot{\rho}_{\rm GRB}$ in a comoving volume is obtained. It is not quite certain whether the observed evolution in luminosity is fully due to the collimation or partially due to the intrinsic evolution in luminosity. So, in this Letter, we use the intermediate case of $\kappa = 0.5$ for simplicity. The resultant rate in units of Gpc$^{-3}$ yr$^{-1}$ is shown in Figure 1 together with the observed data, with the systematic and statistical errors. The typical rate at $z \sim 12$ is roughly $10^4$ Gpc$^{-3}$ yr$^{-1}$ for the case of $\kappa = 0.5$.

### 2.2. *Pop. III SFR*

The absolute GRB rate allows us to estimate the SFR of Pop. III stars with the assistance of the Pop. III IMF. Because of the lack of heavy elements, the IMF for Pop. III stars is likely to be top heavy with massive stars of $\gtrsim 50\ M_\odot$, in contrast to the present-day stars (Abel et al. 2002; Nakamura & Umemura 2001; Tan & McKee 2004). The possible formation of even lower mass Pop. III stars with 1–50 $M_\odot$ is also pointed out (Nakamura & Umemura 2001). But these stars might contribute very little to the UV emission rate or GRB event rate, and therefore they are omitted in the present analysis.

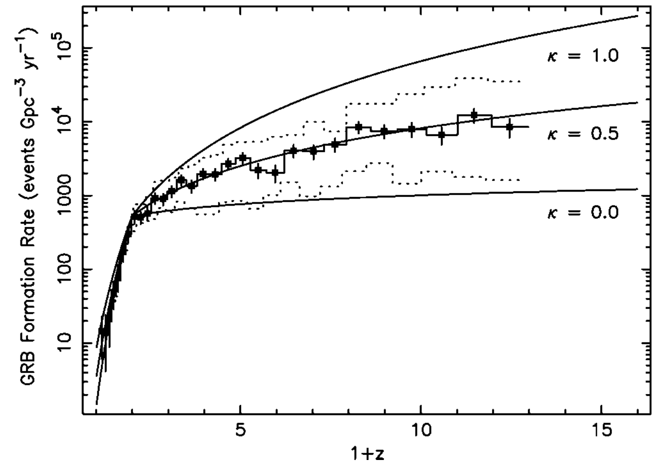


FIG. 1.—Absolute GRB event rate, $\dot{\rho}_{\rm GRB}$, per unit cosmological comoving volume, after the jet-collimation evolution correction. The emission of GRBs is collimated with a typical angle of 0.1 radians (Kulkarni et al. 1999; Frail et al. 2001) and probably shows a cosmological evolution. We estimate the correction of jet collimation with a parameter $\kappa$ as $(1+z)^{2.6\kappa}$, where 2.6 represents the observed luminosity evolution. The squares with error bars are the observed GRB event rates after the jet-collimation evolution correction with $\kappa = 0.5$. The raw data are from Yonetoku et al. (2004). The dotted lines indicate the systematic error of the formation estimate. The three solid lines show the differences of the cosmological jet-collimation angle evolution correction with $\kappa$ = 0, 0.5, and 1.0. No jet-collimation evolution is included in the case of $\kappa = 0$. The rough value of $\dot{\rho}_{\rm GRB}$ is $10^4$ Gpc$^{-3}$ yr$^{-1}$ at $z \sim 12$.

The theory of the stellar evolution of extremely metal-poor ($\lesssim 10^{-4}\ Z_\odot$) stars (Heger et al. 2003) shows that the stars with about 8–40 $M_\odot$ will evolve and explode as Type II SNe, leaving a neutron star or a black hole and ejecting heavy elements into space. The stars with 40–140 $M_\odot$ will produce UV photons during their evolutionary pass, but they will not eject any heavy elements into space because they will collapse completely, forming a black hole. The stars with 140–260 $M_\odot$ will explode as a pair-instability SNe, forming a black hole and ejecting heavy elements into space. Among these stars, we are interested in the stars with 100–140 $M_\odot$, which can result in GRBs as progenitors. This mass range is sometimes called an energetic SN (hypernova). Hence, in metal-poor environments, GRB events occur only in the narrow mass range in the Pop. III IMF.

Here, we employ the Pop. III IMF by Nakamura & Umemura (2001), which is in the form of a double-peaked function with sharp cutoffs and with a power-law shape: $\alpha = \beta = 1.35$ and cutoffs $m_{p1} = 1\ M_\odot$ and $m_{p2} = 50\ M_\odot$, respectively (see Nakamura & Umemura 2001 for details). As stated above, we consider only the high-mass part of the IMF. The normalization factor can be determined by the GRB event rate, $\dot{\rho}_{\rm GRB}$, which corresponds to a mass range of 100–140 $M_\odot$. Then, if the Pop. III fraction $f^{\rm III}_{\rm GRB}$ in the observed GRB rate is given, we can derive the Pop. III SFR in terms of

$$\dot{\rho}^{\rm III}_* \simeq 3 \times 10^2 f^{\rm III}_{\rm GRB} \dot{\rho}_{\rm GRB}\ M_\odot\ {\rm Gpc^{-3}\ yr^{-1}} \quad (1)$$

after an integration over the IMF. Actually, $f^{\rm III}_{\rm GRB}$ is a function of time. Heger et al. (2003) show that the GRB range quickly expands for $Z > 10^{-4}\ Z_\odot$ (Pop. I/II), but simultaneously the IMF is likely to become the present-day–type (Salpeter) IMF for the enriched gas (Bromm et al. 2001). As a result, the mass fraction of GRBs originating from Pop. I/II stars is roughly twice as high as that of Pop. III GRBs. Hence, if $f_*^{\rm III}$ is the fraction of Pop. III stars, the $f_{\rm GRB}^{\rm III}$ is given by

$$f_{\rm GRB}^{\rm III} \simeq 0.5 f_*^{\rm III}/(1 - 0.5 f_*^{\rm III}). \quad (2)$$

It is expected that $f_*^{\rm III}$ is near unity in an early epoch and then decreases with the metal enrichment. Scannapieco et al. (2003) have derived the $f_*^{\rm III}$ as a function of redshift. They have analyzed the dependence of $f_*^{\rm III}$ on the total energy input into outflows from Pop. III ejecta per unit gas mass, $E_g^{\rm III}$ in units of $10^{51}$ ergs $M_\odot^{-1}$. The model with $E_g^{\rm III} = 10^{-4.5}$ roughly corresponds to $f_*^{\rm III} = 40\%$–$50\%$, while the model with $E_g^{\rm III} = 10^{-3.5}$ corresponds to $f_*^{\rm III} = 10\%$. Hence, combining equation (2) with equation (1), it is concluded that the observed GRB event rate implies the continuous formation of Pop. III stars at $4 \leq z \leq 12$.

## 3. REIONIZATION AND ENRICHMENT

### 3.1. *UV Emissivity and Reionization History*

The massive stars with more than 50 $M_\odot$ radiate photons in the blackbody of $\sim 10^5$ K that are energetic enough to ionize neutral hydrogen. Their luminosities should be near the Eddington luminosity (Schaerer 2002), so $\sim 10^{62}(M/M_\odot)$ UV photons are emitted during their lifetime of $\sim 10^6$ yr. For the Pop. III SFR assessed above, we can evaluate the total UV photon emission rate per unit cosmological comoving volume as

$$\dot{\mathcal{N}}_\gamma \simeq 3 \times 10^{62} \dot{\rho}_*^{\rm III} \ {\rm Gpc^{-3}\ yr^{-1}} \quad (3)$$

for stars heavier than 50 $M_\odot$, where $\dot{\rho}_*^{\rm III}$ is given in units of $M_\odot$ Gpc$^{-3}$ yr$^{-1}$. The resultant UV emissivity by Pop. III stars is shown in Figure 2. On the other hand, the UV photon emission rate required to keep ionizing hydrogen in the universe is estimated as $Cn_{\rm H}(z = 0)/t_{\rm rec}$ (Madau et al. 1999), where $C$ is the clumping factor of the IGM and $t_{\rm rec}$ is the recombination time, $t_{\rm rec} = 1100(1 + z)^{-3}(\Omega_b h^2/0.0224)^{-1}$ Gyr. Several authors have argued for the effect of clumpiness on the reionization (Gnedin & Ostriker 1997; Nakamoto et al. 2001; Springel & Hernquist 2003). Since the clumpiness shortens the recombination time in H II regions, then the clumping factor should be estimated by $C = \langle n_{\rm H\,II}^2\rangle/\langle n_{\rm H\,II}\rangle^2$. When all the matter is totally ionized, $C$ becomes equal to the clumping factor of baryons, $C = \langle n_b^2\rangle/\langle n_b\rangle^2$. But, if the IGM is partially ionized so that the density peaks are self-shielded, $C$ is smaller than $\langle n_b^2\rangle/\langle n_b\rangle^2$. Therefore, $C = 1$ corresponds to the requisite minimum level for the IGM ionization, while $C = \langle n_b^2\rangle/\langle n_b\rangle^2$ corresponds to the maximum level. In Figure 2, the UV emission rate for reionization is shown for $C = 1$, and $C = \langle n_b^2\rangle/\langle n_b\rangle^2$, which is taken from Gnedin & Ostriker (1997). The most recent results of *WMAP* suggest a much higher clumping factor than their value, but we should wait for the second *WMAP* results for a more accurate discussion. As seen in Figure 2, the UV photon emission rate inferred from the GRB events exceeds the maximum level for the IGM ionization at all epochs of $7 \leq z \leq 12$, for the $E_g^{\rm III} = 10^{-4.5}$ model or for the Pop. III GRB fraction larger than several tens of percent. However, if the escape fraction of ionizing photons is much smaller than 10%, the photon emission rate can fall below the maximum rate. Especially when larger systems form at lower redshifts in a cold dark matter universe, the escape fraction may be reduced significantly (Kitayama et al. 2004; Whalen et al. 2004). Then the IGM may be neutralized at some redshift. At lower redshifts, Pop. I/II stars would make more contributions to the ionizing photon budget, which may reionize the IGM again.

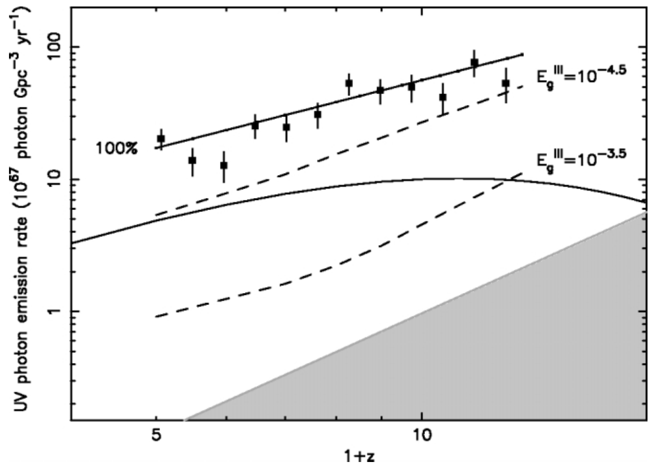


FIG. 2.—UV photon emission rate by Pop. III stars in a comoving volume inferred from the Pop. III GRB event rate. The straight solid line is the emission rate assuming that all GRBs originate from Pop. III stars, where the raw data are plotted with error bars. The two dashed lines show the emission rate using the fractions of Pop. III stars based on the models of Scannapieco et al. (2003) with $E_g^{\rm III} = 10^{-3.5}$ and $E_g^{\rm III} = 10^{-4.5}$, where $E_g^{\rm III}$ is the total energy input into outflows from Pop. III ejecta per unit gas mass. The boundary of the gray region shows the minimum level required to keep ionizing the IGM, assuming a clumping factor of $C = 1$. The solid curve is the requisite maximum level for the IGM ionization, assuming $C = \langle n_b^2\rangle/\langle n_b\rangle^2$ based on the simulation by Gnedin & Ostriker (1997).

### 3.2. *Early Enrichment of IGM*

Next, we consider the enrichment by heavy elements synthesized in Pop. III objects. Since the amount of mass ejection from energetic SNe (hypernovae) and from pair-instability SNe into space is very roughly $\sim 0.1$ and $\sim 0.5$ of the initial mass for 100–140 and 140–260 $M_\odot$, respectively (Heger et al. 2003), we can estimate the heavy-element production rate into the IGM as $0.3\dot{\rho}_*^{\rm III}$ $M_\odot$ Gpc$^{-3}$ yr$^{-1}$. Using the Pop. III SFR, the metallicity of the IGM enriched by Pop. III stars is estimated to be $2.2 \times 10^{-4}\ Z_\odot$ for $E_g^{\rm III} = 10^{-3.5}$ and $1.2 \times 10^{-3}\ Z_\odot$ for $E_g^{\rm III} = 10^{-4.5}$. The model with $E_g^{\rm III} = 10^{-4.5}$ appears to overproduce the IGM metals, if compared to $\sim 10^{-4}\ Z_\odot$ at $z \sim 5.3$ (Songaila 2001). However, it should be noted that all synthesized metals cannot be spread out from Pop. III objects (Norman et al. 2004). Then, even the model with $E_g^{\rm III} = 10^{-4.5}$ may not provide sufficient metals for the IGM metallicity.

## 4. CONCLUSIONS AND DISCUSSION

In this Letter, we have estimated the absolute GRB event rate out to $z \sim 12$ observationally with the correction for collimation. There have also been several efforts to estimate a GRB event rate in the early universe, using the independent method (Murakami et al. 2003; Fenimore & Ramirez-Ruiz 2000; Schaefer et al. 2001). All the results are broadly consistent with each other and show that there is no break in the GRB event rate as a function of redshift.

Based on the GRB event rate, we have found that Pop. III stars could form continuously at $4 \leq z \leq 12$. This implies that Pop. III star formation is not likely to be strongly suppressed in early epochs. This is qualitatively consistent with the recent study on the star formation history in dwarf spheroidal galaxies in the Local Group, which shows continuous star formation even after reionization (Grebel & Gallagher 2004). Also, in recent theoretical studies, it is shown that dwarf galaxies can form as a result of self-shielding even during reionization (Susa & Umemura 2004) and that star formation can be induced by an SN-driven shock (Mori et al. 2004).

As for reionization, it has been found that the UV emission from Pop. III stars can make a noticeable contribution to early reionization. If the escape fraction of ionizing photons is large enough, then the UV emission from Pop. III stars can keep ionizing the IGM at $7 \leq z \leq 12$. But if it is smaller, it can lead to the re-neutralization of the IGM at some redshift, which may result in the double reionization (Cen 2003b; Wyithe & Loeb 2004). Regarding the enrichment, a high Pop. III fraction in high-$z$ GRBs may lead to the overproduction of IGM metals if all synthesized metals are spread out into intergalactic space. But if they are confined around Pop. III objects, it may be difficult to account for IGM metals solely by Pop. III stars.

Finally, it is noted that there still remain a few less robust factors in this type of analysis. The most unknown factor is the validity of the spectral peak energy-to-luminosity relation for GRBs out to $z \sim 12$. Although Yonetoku et al. (2004) derived a firm relation out to about $z \sim 5$ based on the observed redshifts, this relation to higher redshifts is not confirmed. The second factor is the correction for collimation of GRBs. GRBs are really collimated, but we do not know the degree of collimation in luminosities for GRBs at $z > 5$. These should be confirmed by detecting GRBs out to $z \sim 10$ with the *Swift* GRB mission. Also, we should check the consistency of the obtained Pop. III SFR with the infrared background.

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