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HIGH-REDSHIFT GAMMA-RAY BURSTS FROM POPULATION III PROGENITORS

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ABSTRACT

Detection of gamma-ray bursts (GRBs) from redshifts $z \gtrsim 7$ would open a new window into the earliest epoch of cosmic star formation. We construct separate star formation histories at high redshifts for normal (Population I and II) stars and for predominantly massive (Population III) stars. Based on these separate histories, we predict the GRB redshift distribution to be observed by the *Swift* mission. Regardless of whether Population III progenitors are able to trigger GRBs, we find that a fraction, ~10%, of all bursts detected by *Swift* will originate at $z \gtrsim 5$. This baseline contribution is due to Population I/II star formation, which must have extended out to high redshifts in rare massive galaxies that were enriched by heavy elements earlier than the typical galaxies. In addition, we consider the possible contribution of Population III progenitors to the observable GRB rate. Population III stars are viable progenitors for long-duration GRBs that are triggered by the collapsar mechanism, as long as they can lose their outer envelope through mass transfer to a companion star in a close binary. We find that the likelihood of Population III binaries to satisfy the conditions required by the collapsar mechanism could be enhanced significantly relative to Population I/II binaries. If Population III binaries are common, *Swift* will be the first observatory to probe Population III star formation at redshifts $z \gtrsim 7$.

Subject headings: binaries: general — cosmology: theory — gamma rays: bursts — stars: formation

1. INTRODUCTION

The first stars in the universe, so-called Population III, formed out of metal-free gas at the end of the cosmic dark ages or redshifts $z \gtrsim 10$ (for reviews, see, e.g., Barkana & Loeb 2001; Bromm & Larson 2004; Ciardi & Ferrara 2005; Glover 2005). These stars are predicted to have been predominantly very massive, with $M_* \gtrsim 100\ M_\odot$ (Bromm et al. 1999, 2002; Abel et al. 2002; Nakamura & Umemura 2001), and to have left a mark on the thermal and chemical evolution of the intergalactic medium (IGM). First, their predicted high surface temperatures (e.g., Bond et al. 1984) imply that they may have been efficient sources of ionizing photons (e.g., Tumlinson & Shull 2000; Bromm et al. 2001b; Schaerer 2002). A contribution from Population III stars to the reionization of the IGM may be required to account for the large optical depth to Thomson scattering inferred by the *Wilkinson Microwave Anisotropy Probe* (*WMAP*; Kogut et al. 2003) during its first year of operation (e.g., Cen 2003; Wyithe & Loeb 2003a, 2003b). Second, since the stellar evolutionary timescale for massive Population III stars is short, $\sim 10^6$ yr, the resulting initial enrichment of the IGM with heavy elements could have occurred rather promptly (e.g., Mori et al. 2002; Bromm et al. 2003; Wada & Venkatesan 2003; Yoshida et al. 2004).

Gamma-ray bursts (GRBs) offer unique prospects for probing the cosmic star formation (Totani 1997; Wijers et al. 1998; Blain & Natarajan 2000; Porciani & Madau 2001; Bromm & Loeb 2002; Hernquist & Springel 2003; Mesinger et al. 2005; Natarajan et al. 2005), as well as the IGM (Loeb 2005; Barkana & Loeb 2004; Gou et al. 2004; Inoue et al. 2006; Ioka & Mészáros 2005), at redshifts $z \gtrsim 7$, beyond the current horizon of galaxy and quasar surveys. GRBs are the brightest electromagnetic explosions in the universe (for recent reviews, see van Paradijs et al. 2000; Mészáros 2002; Piran 2005), and their emission is detectable out to $z \gtrsim 10$. The detectability of their gamma-ray emission (Lamb & Reichart 2000) allows simultaneous monitoring of a major portion of the sky, while the detectability of their afterglow (Ciardi & Loeb 2000) allows determination of their high redshift from the appearance of the intergalactic Lyα absorption trough in the infrared (Loeb 2005; Barkana & Loeb 2004). The popular collapsar model for the central engine of long-duration GRBs (MacFadyen et al. 2001 and references therein) involves the collapse of a massive star to a black hole (BH). This model naturally explains the observed association of long-duration GRBs with star-forming regions (e.g., Fruchter et al. 1999; Djorgovski et al. 2001; Bloom et al. 2002a) and the Type Ib/c supernova signature on the spectra of rapidly decaying afterglow light curves (e.g., Bloom et al. 2002b; Hjorth et al. 2003; Matheson et al. 2003; Stanek et al. 2003).

Because of their high characteristic masses, Population III stars could potentially lead to high-redshift GRBs. The recently launched *Swift* satellite[3] (Gehrels et al. 2004) is ideally suited to utilize this novel window into the high-redshift universe. In the following sections we address the underlying question: Which fraction of high-redshift bursts could originate from Population III progenitors? The actual fraction and distribution of high-*z* GRBs to be measured by *Swift* might reflect the absence or presence of the potential Population III contribution.

The organization of the paper is as follows. In § 2 we describe our cosmic star formation model, in particular determining the Population III mode at the highest redshifts. The resulting GRB redshift distribution is calculated in § 3, which also includes a discussion of plausible GRB progenitors. Finally, we address the implications of our results in § 4.

2. STAR FORMATION MODES AT HIGH REDSHIFTS

We note that GRBs are expected to exist at redshifts $z \gtrsim 7$ even in the absence of any true Population III contribution. This is due to the rapid enrichment of the IGM with heavy elements dispersed by the first supernovae (SNe) beginning at $z \gtrsim 20$ (e.g., Loeb & Haiman 1997; Madau et al. 2001; Bromm et al.

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[3] See http://swift.gsfc.nasa.gov.

2003; Furlanetto & Loeb 2003; Scannapieco et al. 2003). Once a given region of the universe has been enriched beyond a critical metallicity, $Z_{\rm crit} \sim 10^{-3.5}\ Z_{\odot}$, the mode of star formation is predicted to shift from high-mass Population III stars to the lower mass Population I and II cases (e.g., Omukai 2000; Bromm et al. 2001a; Schneider et al. 2002, 2003; Bromm & Loeb 2003b; Mackey et al. 2003). The mass fraction of supercritical gas is rapidly growing toward lower redshift, and GRBs could be formed in the conventional way from metal-enriched Population I and II progenitors at high z. In the following discussion, we first construct the total cosmic star formation rate (SFR) and subsequently decompose the total SFR into separate Population I/II and Population III components.

2.1. *Star Formation History*

Our model for the total cosmic SFR closely follows that of Bromm & Loeb (2002), and here we only briefly describe the key assumptions. The abundance and merger history of the cold dark matter (CDM) halos is described by the extended Press-Schechter formalism (Lacey & Cole 1993). We assume that the IGM has a two-phase structure, consisting of neutral and ionized hydrogen phases. The reionization of the IGM was likely an extended process, occurring over $6 \lesssim z \lesssim 20$ (e.g., Cen 2003; Wyithe & Loeb 2003a; Sokasian et al. 2004; Furlanetto & Loeb 2005). To bracket the possibilities, we consider two reionization redshifts, $z_{\rm reion} \approx 7$ and 17, where $z_{\rm reion}$ corresponds to an ionization filling fraction by volume of ~50%. In each case, reionization is spread out over a range in redshifts, $\Delta z/(1+z) \simeq 1$.

Within each phase of the IGM, stars are able to form in two different ways. The first mechanism pertains to primordial, metal-free gas. Such gas undergoes star formation provided that it accretes onto a dark matter halo with a sufficiently deep gravitational potential well or, equivalently, a mass above a minimum value. For the neutral medium, this minimum mass is set by the requirement that the gas will be able to cool. Radiative cooling by molecular hydrogen (H_2) allows star formation in halos with a virial temperature $T_{\rm vir} \gtrsim 500$ K, while atomic cooling dominates for halos with $T_{\rm vir} \gtrsim 10^{3.9}$ K. Since H_2 can be easily photodissociated by photons below the Lyman limit, its significance in the cosmic star formation history is unclear (e.g., Bromm & Larson 2004 and references therein), so we only show results without H_2 cooling in this paper. We note, however, that in the limiting case of negligible H_2 photodissociation feedback, the cosmic star formation rate at $z \gtrsim 15$ could be larger by 1 order of magnitude than the purely atomic cooling case discussed here.

For the ionized medium, on the other hand, the minimum threshold mass is given by the Jeans mass, since the infall of gas and the subsequent formation of stars requires that the gravitational force of the dark matter halo be greater than the opposing pressure force on the gas. After reionization, the IGM is photoheated to temperatures $\gtrsim 10^4$ K, leading to a dramatic increase in the Jeans mass. We model the suppression of gas infall according to results from spherically symmetric collapse simulations (see Bromm & Loeb 2002 for details). In calculating the late reionization case ($z_{\rm reion} \approx 7$), we employ the prediction by Thoul & Weinberg (1996) that gas infall is completely suppressed in halos with circular velocities $v_c \lesssim 35$ km s^{-1}. For the early reionization case ($z_{\rm reion} \approx 17$), however, we use the recent work by Dijkstra et al. (2004), showing that the infall suppression due to photoionization heating could be much less severe in the high-redshift universe. Specifically, we assume that in this latter case infall is completely suppressed only in halos with circular velocities $v_c \lesssim 10$ km s^{-1}.

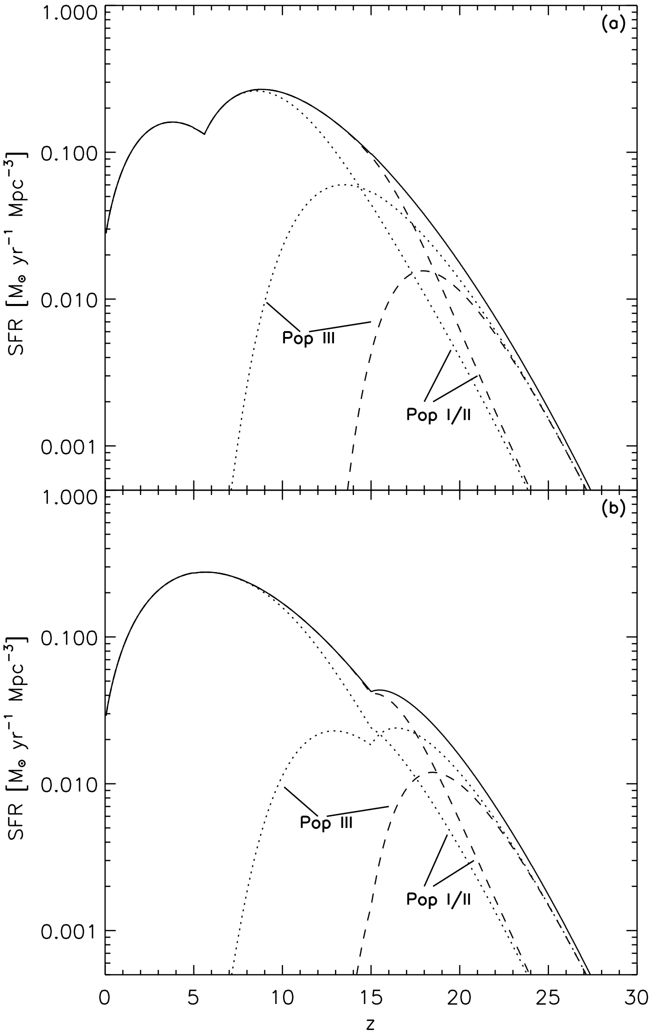

FIG. 1.—Cosmic comoving SFR in units of solar masses per year per cubic megaparsec as a function of redshift. We assume that cooling in primordial gas is due to atomic hydrogen only and that the star formation efficiency is $\eta_* = 10\%$. (*a*) Late reionization ($z_{\rm reion} \approx 7$). *Solid line*: Total comoving SFR. *Dotted lines*: Contribution to the total SFR from Population I/II and Population III for the case of weak chemical feedback. *Dashed lines*: Contribution to the total SFR from Population I/II and Population III for the case of strong chemical feedback. (*b*) Early reionization ($z_{\rm reion} \approx 17$). We adopt the same convention for the lines as in panel (*a*). In all cases, Population III star formation is restricted to high redshifts but extends over a significant range, $\Delta z \sim 10$–15.

Within our model, the second mechanism to form stars occurs in gas that has experienced a previous burst of star formation and is therefore already somewhat enriched with heavy elements. Such gas, residing in a halo of mass M_1, can undergo induced star formation triggered by a merger with a sufficiently massive companion halo of mass $M_2 > 0.5M_1$. We finally assume that stars form with an efficiency of $\eta_* \sim 10\%$, independent of redshift and regardless of whether the gas is primordial or preenriched. This efficiency yields roughly the correct fraction of Ω_B found in stars in the present-day universe. Figure 1 shows the resulting total star formation histories. It is evident that there are two distinct epochs of cosmic star formation, one at $z \sim 3$ and a second at $z \sim 8$ for late reionization, whereas there is only a single, extended peak at $z \sim 5$ for early reionization.

2.2. *Population III Star Formation*

To determine the fraction of the total SFR contributed by Population III stars, we have to identify those halos that cross the atomic cooling threshold for the first time. In addition, we require that the collapse takes place in a region of the IGM that is not yet enriched with heavy elements from previous episodes of star formation. Here we adopt the formalism developed in Furlanetto & Loeb (2005), who derived the redshift-dependent probability that a newly collapsed halo forms out of pristine gas (see their Fig. 2). This probability crucially depends on the efficiency with which the newly created metals are dispersed into the IGM via SN-driven winds. To bracket the range of possibilities, we consider the cases of weak and strong chemical feedback, corresponding to winds experiencing large and small radiative losses, respectively.[4]

As can be seen in Figure 1, Population III star formation is limited to the highest redshifts but in each case extends over a substantial range in redshift: $\Delta z \sim 10$ for strong chemical feedback and ~ 15 for weak feedback. The Population III histories are rather similar for both early and late reionization. The suppression of gas infall for the early reionization case (with $v_c \lesssim 10\ \mathrm{km\ s^{-1}}$) would have a much more pronounced effect on halos that cool via H_2 because of their shallower potential wells.

3. GRB REDSHIFT DISTRIBUTION

Next we predict the GRB redshift distribution for flux-limited surveys, distinguishing between the contributions from Population I/II and Population III star formation. In particular, we focus on the existing *Swift* satellite, which is capable of making the most detailed determination of the GRB redshift distribution to date.

3.1. *Population I/II Contribution*

Assuming that the formation of GRBs closely follows the cosmic star formation history with no cosmologically significant time delay (e.g., Conselice et al. 2005), we write for the number of all GRB events per comoving volume per time, regardless of whether they are observed or not, $\psi_{\rm GRB}^{\rm true}(z) = \eta_{\rm GRB}\psi_*(z)$, where $\psi_*(z)$ is the cosmic SFR, as calculated in § 2. The efficiency factor, $\eta_{\rm GRB}$, links the formation of stars to that of GRBs and is in principle a function of redshift, as well as of the properties of the underlying stellar population. The stellar initial mass function (IMF) is predicted to differ fundamentally for Population I/II and Population III (e.g., Bromm & Larson 2004 and references therein). The GRB efficiency factor will depend on the fraction of stars able to form BHs and consequently on the IMF (see § 3.2). Here we assume that $\eta_{\rm GRB}$ is constant with redshift for Population I/II star formation, whereas Population III stars may be characterized by a different efficiency.

The number of bursts detected by any given instrument depends on the instrument-specific flux sensitivity threshold and on the poorly determined isotropic luminosity function (LF) of GRBs (see, e.g., Schmidt 2001; Sethi & Bhargavi 2001; Norris 2002). In order to ascertain what *Swift* is expected to find, we modify the true GRB event rate as follows:

$$\psi_{\rm GRB}^{\rm obs}(z) = \eta_{\rm GRB}\psi_*(z)\int_{L_{\rm lim}(z)}^{\infty} p(L)\,dL. \qquad (1)$$

Here $p(L)$ is the GRB LF, where L is the intrinsic, isotropic-equivalent photon luminosity (in units of photons per second). If $f_{\rm lim}$ denotes the sensitivity threshold of a given instrument (in photons per second per square centimeter), then the minimum luminosity is

$$L_{\rm lim}(z) = 4\pi d_L^2 f_{\rm lim}(1+z)^{\alpha-2}, \qquad (2)$$

where d_L is the luminosity distance to a source at redshift z and α the intrinsic high-energy spectral index (Band et al. 1993). For definiteness, we assume $\alpha = 2$, which gives a reasonable fit to the observed burst spectra (see Band et al. 1993 for a detailed discussion). We here use the same lognormal LF and the same parameters as described in Bromm & Loeb (2002).

In Bromm & Loeb (2002), we predicted that $\sim$25% of all bursts observed by *Swift* would originate at $z \geq 5$. This estimate was based on a flux threshold of $f_{\rm lim} = 0.04$ photons $\mathrm{s^{-1}\ cm^{-2}}$. Based on the first few months of actual observations by *Swift*, the sensitivity limit has recently been revised upward to $f_{\rm lim} = 0.2$ photons $\mathrm{s^{-1}\ cm^{-2}}$, comparable to the older Burst and Transient Source Experiment (BATSE; e.g., Berger et al. 2005). Using this revised flux limit, we predict that $\sim$10% of all *Swift* GRBs will originate at $z \geq 5$.

Over a particular time interval $\Delta t_{\rm obs}$ in the observer frame, the observed number of GRBs originating between redshifts z and $z + dz$ is

$$\frac{dN_{\rm GRB}^{\rm obs}}{dz} = \psi_{\rm GRB}^{\rm obs}(z)\frac{\Delta t_{\rm obs}}{(1+z)}\frac{dV}{dz}, \qquad (3)$$

where dV/dz is the comoving volume element per unit redshift (see Bromm & Loeb 2002). As a final step, we normalize the GRB formation efficiency per unit mass in Population I/II stars to $\eta_{\rm GRB} \simeq 2 \times 10^{-9}$ GRBs per solar mass. This choice results in a predicted number of $\sim$90 GRBs per year detectable by *Swift*. In Figure 2, we show the *Swift* GRB rate, associated with Population I/II star formation. For both early and late reionization, the observed distribution is expected to peak around $z \sim 2$. This distribution is broadly consistent with the first GRB redshifts, still limited in number, measured during the first months of the *Swift* mission (Berger et al. 2005). We now turn to the possible contribution to the high-redshift GRB rate from Population III stars.

3.2. *Population III Contribution*

We begin by assuming that Population III star formation gives rise to GRBs with the same (constant) efficiency as is empirically derived for Population I/II stars. As is evident from Figure 2, only for the case of weak chemical feedback is *Swift* expected to detect a few bursts deriving from Population III progenitors over the $\sim$5 yr lifetime of the mission. Whether reionization occurred early or late, on the other hand, has only a small effect on the predicted rates. It is quite possible, therefore, that *Swift* will not detect any Population III GRBs at all. Regardless of the uncertain contribution from Population III stars, however, the prediction that $\sim$10% of all *Swift* bursts originate at $z \geq 5$ is rather robust. This fraction is due to Population I/II progenitors that are known to produce GRBs, and those should exist at $z \geq 5$.

Adopting the same $\eta_{\rm GRB}$ for Population III as for Population I/II, however, could be significantly in error. To examine the fundamental difference between the stellar populations, we need to go beyond the phenomenological approach pursued so far and discuss the properties of plausible GRB progenitors in greater physical detail.

3.2.1. *Collapsar Engine*

Existing evidence implies that long-duration bursts are related to the death of a massive star, leading to the formation of a

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[4] The weak and strong feedback cases correspond to $K_w^{1/3} = \frac{1}{3}$ and 1 in eq. (4) of Furlanetto & Loeb (2005).

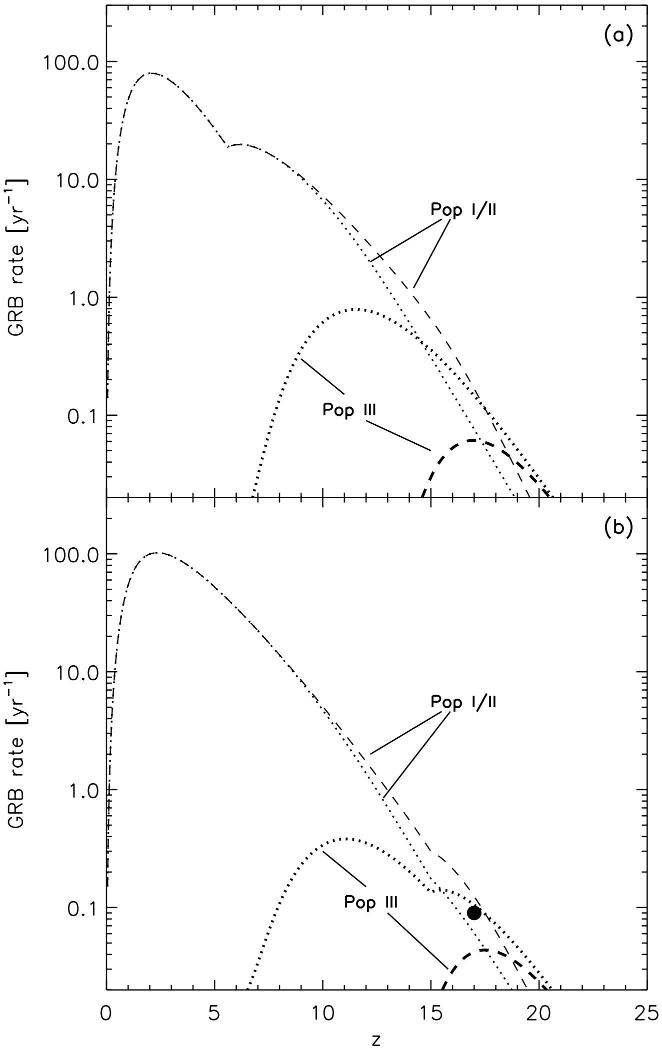

FIG. 2.—Predicted GRB rate observed by *Swift*. Shown is the observed number of bursts per year, $dN^{\rm obs}_{\rm GRB}/d\ln(1+z)$, as a function of redshift. All rates are calculated with a constant GRB efficiency, $\eta_{\rm GRB} \simeq 2\times10^{-9}$ bursts per solar mass, using the cosmic SFRs from Fig. 1. (*a*) Late reionization ($z_{\rm reion} \approx 7$). *Dotted lines*: Contribution to the observed GRB rate from Population I/II and Population III for the case of weak chemical feedback. *Dashed lines*: Contribution to the GRB rate from Population I/II and Population III for the case of strong chemical feedback. (*b*) Early reionization ($z_{\rm reion} \approx 17$). The lines have the same meanings as in panel (*a*). *Filled circle*: GRB rate from Population III stars if these were responsible for reionizing the universe at $z \sim 17$ (see text). The GRB rates from Population III progenitors are very uncertain; they could be zero or, in the other extreme, display an enhancement by up to 1 order of magnitude above the baseline rates shown here (see text for details).

BH (see review by Piran 2005). The popular collapsar model assumes that an accretion torus is temporarily formed around the black hole and that the gravitational energy released during the accretion is able to power a strong explosion (e.g., Woosley 1993; Lee & Ramirez-Ruiz 2006). For the collapsar to result in a GRB, additional requirements have to be met beyond the formation of a BH. We discuss these next and then explore whether a subset of Population III stars could successfully launch a GRB under the collapsar scenario.

To successfully produce a GRB with a collapsar, three basic requirements have to be fulfilled (see, e.g., Zhang & Fryer 2004; Petrovic et al. 2005):

1. The progenitor star has to be sufficiently massive to result in the formation of a central BH. Collapse to a BH could occur either directly for initial masses of the progenitor $\gtrsim 40\ M_\odot$ or in a delayed fashion by fallback of the ejecta following a failed SN explosion for progenitor masses $25\ M_\odot \lesssim M_* \lesssim 40\ M_\odot$ (e.g., Heger et al. 2003). The number of BH-forming stars resulting from a given total stellar mass, here denoted by $\eta_{\rm BH}$, will depend on the stellar IMF, which in turn is predicted to differ between the Population I/II and Population III cases.

For simplicity, we assume that the IMF in both cases consists of a power law with the standard Salpeter value, $dN/dm \propto m^{-2.35}$, but with different values for the lower and upper mass limits, $M_{\rm low}$ and $M_{\rm up}$, respectively. For Population I/II stars, we take these to be $M_{\rm low} = 0.1\ M_\odot$ and $M_{\rm up} = 100\ M_\odot$. The Population III IMF, on the other hand, is still very uncertain (see, e.g., Bromm & Larson 2004). The upper mass limit can be conservatively estimated to be $M_{\rm up} \sim 500\ M_\odot$ (Bromm & Loeb 2004), whereas for the lower limit, we consider two possibilities: $M_{\rm low} \sim 30$ (e.g., Tan & McKee 2004) and $\sim 100\ M_\odot$ (e.g., Abel et al. 2002; Bromm et al. 2002).

In general,

$$\eta_{\rm BH} = \frac{\int_{M_{\rm BH}}^{M_{\rm up}} m^{-2.35}\,dm}{\int_{M_{\rm low}}^{M_{\rm up}} m^{-1.35}\,dm}, \tag{4}$$

where $M_{\rm BH} \simeq 25\ M_\odot$. For the Population I/II case, this results in $\eta_{\rm BH} \simeq 1/(700\ M_\odot)$. The Population III lower mass limit exceeds the threshold for BH formation in either case, $M_{\rm low} > M_{\rm BH}$. Not *every* Population III star, however, will leave a BH behind. In the narrow mass range of $\sim$140–260 $M_\odot$, Population III stars are predicted to undergo a pair-instability supernova (PISN) explosion (e.g., Fryer et al. 2001; Heger et al. 2003). A PISN will lead to the complete disruption of the star, such that no compact remnant will be left behind. For the Population III case, the expression results in $\eta_{\rm BH} \simeq 1/(80\ M_\odot)$ for $M_{\rm low} = 30\ M_\odot$ and $\eta_{\rm BH} \simeq 1/(300\ M_\odot)$ for $M_{\rm low} = 100\ M_\odot$. Thus, the BH formation efficiency is larger for Population III compared to Population I/II by up to 1 order of magnitude, depending on the lower mass limit.

2. The progenitor star has to be able to lose its hydrogen envelope in order for the relativistic outflow to penetrate through and exit the star (e.g., Zhang et al. 2004). This requirement derives from the observed burst durations, $t \lesssim 100$ s, providing an estimate for the lifetime of the central GRB engine. The jet can therefore only travel a distance of $r \sim ct \sim 50\ R_\odot$ before being slowed down to nonrelativistic speeds. Massive stars with hydrogen envelopes grow to a large size during their later evolutionary phases. For example, red supergiants can reach radii of up to $\sim 10^3\ R_\odot$ (e.g., Kippenhahn & Weigert 1990). The effectiveness of mass loss crucially depends on metallicity (e.g., Kudritzki 2002) and on whether the star is isolated or part of a binary system. Below, we discuss both effects further.

3. The progenitor star has to contain a central core with sufficient angular momentum to allow an accretion disk to form around the growing BH. Important aspects of stellar structure and evolution can be understood by dividing the star into a compact core and an extended outer envelope (e.g., Kippenhahn & Weigert 1990). Depending on the evolutionary stage, a radiative core is surrounded by a convective envelope, or vice versa. The precollapse stellar core has a mass M_c, radius R_c, angular velocity ω_c, and is characterized by a specific angular momentum $j_c \simeq R_c^2\omega_c$. Assuming that the collapse to a BH conserves specific angular momentum, the condition for an accretion torus to form around a growing BH in the center with mass $M_{\rm BH}$ is

centrifugal support for material orbiting at the last stable radius. This condition can be expressed as $j_c \gtrsim j_{\rm min}$, with $j_{\rm min} = \sqrt{6}GM_{\rm BH}/c \simeq 3 \times 10^{16}$ cm^2 s^{-1} (e.g., Podsiadlowski et al. 2004).

Recent results obtained with sophisticated stellar evolution codes that include the effects of magnetic torques (e.g., Spruit 2002; Heger et al. 2005) have demonstrated the difficulty of identifying progenitor systems for collapsar-driven GRBs that fulfill both conditions 2 and 3. The basic problem is that the removal of the extended H envelope is accompanied by the loss of angular momentum in the core (e.g., Petrovic et al. 2005). We explore this problem next, first for single-star progenitors and then for binaries.

3.2.2. *Single-Star Progenitor*

In massive Population I/II stars, radiation-driven winds can lead to vigorous mass loss, in which the main source of opacity is provided by metal lines (e.g., Kudritzki & Puls 2000). Empirically, the existence of Wolf-Rayet (W-R) stars proves that Population I/II stars can indeed experience catastrophic mass loss, leading to the removal of the entire hydrogen envelope and, in extreme cases, even of the helium envelope. The violent mass loss, however, is accompanied by the effective removal of angular momentum from the remaining precollapse core, rendering the creation of a collapsar impossible.

For massive Population III stars, radiatively driven winds are predicted to be unimportant (e.g., Kudritzki 2002; Krtička & Kubát 2006). Alternatively, mass loss could occur as a result of stellar pulsations (through the ϵ mechanism). Simplified, linear calculations, however, indicate that this mechanism is not important below $\sim$500 $M_\odot$ (Baraffe et al. 2001). There still remains an unexplored possibility that Population III stars could experience significant mass loss driven by radiation pressure on He$^+$ ions, for which the opacity is provided by bound-free transitions. Alternatively, processed material from preceding episodes of nuclear burning could be transported to the stellar surface by convection, rotationally induced mixing, and diffusion, thus enriching the atmosphere to $Z \gtrsim 10^{-4}$ $Z_\odot$, at which point line-driven mass loss is predicted to set in (Kudritzki 2002; Marigo et al. 2003). Recently, it has been suggested that W-R–type winds, in connection with rapid rotation and the approach to the Eddington limit, could possibly lead to significant mass loss even for very low metallicity stars (Vink & de Koter 2005). The most likely expectation, however, is that isolated massive Population III stars are not able to shed much mass prior to their final collapse.

Thus, it appears likely that the majority of massive, single-star progenitors, for both Population I/II and III, cannot give rise to a collapsar-driven GRB, although for different physical reasons. We note, however, that the progenitor for the collapsar engine is still very uncertain. In addition to the binary scenario (see below), massive, rapidly rotating single stars have recently been considered (e.g., Yoon & Langer 2005; Woosley & Heger 2006). Our main results, based on the cosmic Population III SFR and the IMF-dependent BH fraction, however, hold in this case as well. We next turn our attention to binary-star progenitors.

3.2.3. *Binary-Star Progenitor*

Close binary systems provide a promising avenue to simultaneously meet the requirements of strong mass loss combined with the retention of sufficient angular momentum in the collapsing core (e.g., Lee et al. 2002; Izzard et al. 2004). For Population I/II, a binary pathway to a collapsar-driven GRB has already been suggested (e.g., Fryer et al. 1999). The basic idea is that a close binary system, experiencing Roche lobe overflow (RLOF) when the primary evolves off the main sequence, will go through a common-envelope (CE) phase (e.g., Belczynski et al. 2004), during which the hydrogen envelope of the primary can be removed without seriously draining away the spin of the remaining helium core (for a recent review, see Taam & Sandquist 2000). During the CE phase, the binary will spiral closer together, and the corresponding loss of orbital energy will heat the envelope with a given efficiency, often assumed to be very high: $\alpha_{\rm CE} \simeq 1.0$ (Taam & Sandquist 2000). The frictional energy release during the inspiral phase has been shown to be sufficient to unbind the hydrogen envelope.

For a progressively tightening binary, the spin of each component is tidally coupled to the orbital motion: $\omega_c \sim \omega_{\rm orb}$. Since the helium core is spun up again because of the spin-orbit coupling, it is able to retain sufficient angular momentum to fulfill the $j_c \gtrsim j_{\rm min}$ requirement.

3.2.4. *GRB Formation Efficiency*

In general, we can express the GRB formation efficiency for Population III stars as $\eta_{\rm GRB} \simeq \eta_{\rm BH}\eta_{\rm bin}\eta_{\rm close}\eta_{\rm beaming}$, where $\eta_{\rm bin}$ is the binary fraction, $\eta_{\rm close}$ is the fraction of sufficiently close binaries to undergo RLOF, and $\eta_{\rm beaming} \simeq 1/50$–$1/500$ is the beaming factor, where we conservatively assume that Population III bursts are collimated by the BH central engine to the same angle as in Population I/II progenitors. (The inferred collimation angles by Frail et al. [2001] and Panaitescu & Kumar [2001] are indeed comparable to those of radio jets from the much more massive BHs in galactic nuclei.) We have already discussed $\eta_{\rm BH}$ and how Population III star formation is characterized by an enhancement of up to 1 order of magnitude because of the higher fraction of BH-forming progenitors.

It is currently not known whether Population III stars can form binaries and, if so, what the corresponding binary fraction would be (e.g., Saigo et al. 2004). In present-day star formation, the incidence of binaries is high, with $\sim$50% of all stars occurring in binaries or small multiple systems (e.g., Duquennoy & Mayor 1991). Current three-dimensional simulations of the formation of the first stars still lack the resolution to resolve the possible fragmentation of a collapsing cloud into *tight* binaries or multiple stellar cores on scales $\lesssim$100 AU. Although we cannot yet conclusively address the formation of close binaries, there is evidence from numerical simulations that binary or multiple clump formation is rather common on larger scales ($\gtrsim$0.1 pc). In simulations in which the collapsing gas had acquired a high degree of angular momentum and in which the collapse led to a disklike configuration, prestellar clumps commonly occurred in binary or multiple systems (e.g., Bromm et al. 1999, 2002; Bromm & Loeb 2003a, 2004). Thus motivated, our best guess is that $\eta_{\rm bin} \lesssim 0.5$. More work, in particular involving improved numerical simulations, is required to constrain this crucial quantity further.

Provided that Population III star formation does include a fraction of binaries, we can use the collapsar requirements to obtain an estimate for the maximum binary separation, $a_{i,\rm max}$, prior to the CE inspiral phase, as follows. Assuming for simplicity that a Population III binary has equal-mass components, the Roche radius is $r_L \sim 0.5a_i$. A CE phase will only occur when the star overflows its Roche lobe during the red giant phase: $R_{\rm RG} > r_L \gtrsim a_i$. We estimate the Population III radius during the giant phase, which is smaller than that of a Population I star of equal mass, to be $R_{\rm RG} \sim 300R_{\rm MS}$, where $R_{\rm MS}$ is the main-sequence radius. Massive Population III stars obey a simple mass-radius relation (Bromm et al. 2001b): $M \propto R_{\rm MS}^2$. The maximum separation for RLOF and therefore a CE phase to occur is thus

$$a_{i,\max} \simeq \left(10^3\ R_\odot\right)\left(\frac{M}{10^2\ M_\odot}\right)^{1/2}. \tag{5}$$

The minimum possible binary separation, $a_{i,\min}$, on the other hand, will determine the extent of the inspiral process and therefore of the accompanying frictional heating of the hydrogen envelope, as well as the tidal spinning up of the helium core. We approximately assume that the minimum separation is given by twice the radius of a massive Population III star during the main-sequence phase (which is only weakly dependent on mass): $a_{i,\min} \simeq 10\ R_\odot$. If we further assume that the initial separations are distributed with equal probability per logarithmic separation interval, as they are for Population I/II binaries (e.g., Abt 1983; Heacox 1998; Larson 2003), $dN/d\ln a \propto$ constant, and that the largest possible binary separation is given by the Jeans length for the typical conditions in a primordial gas cloud, $\lambda_J \simeq 1$ pc (e.g., Bromm et al. 2002; Bromm & Loeb 2004), we estimate the fraction of all Population III binaries that are sufficiently close to experience a CE phase to be $\eta_{\rm close} \sim 30\%$.

In summary, $\eta_{\rm GRB}$ for Population III stars is very uncertain and could be zero in the case that no Population III binaries existed. On the other hand, one can argue that the binary properties for Population III had been similar to Population I/II, in cases in which Population III star formation takes place in more massive host systems that could give rise to a stellar cluster or at least multiple stars. Such a clustered environment is often suggested to explain the formation and the properties of binaries in present-day galaxies (e.g., Larson 2003). Assuming that the Population III binary properties are similar to those of Population I/II, we find a significant enhancement in $\eta_{\rm BH}$ due to the difference in the IMF between the populations. We can then place an upper limit on the GRB rate from Population III stars by multiplying the baseline rates in Figure 2 by a factor of $\sim$10. This would result in Population III GRB rates as large as $\sim$10 bursts detected by *Swift* per year for the case of weak chemical feedback. Such very high rates can already be excluded, since *Swift* has only identified two GRBs from $z \gtrsim 5$ as of yet, GRB 050814 at $z \simeq 5.3$ (Jakobsson et al. 2006) and GRB 050904 at $z \simeq 6.3$ (Antonelli et al. 2005; Haislip et al. 2005; Kawai et al. 2005). For strong chemical feedback, on the other hand, we predict rates of less than one burst detected per year, even if the BH efficiency were increased by 1 order of magnitude, and such a Population III contribution cannot be excluded with the current constraints from *Swift*.

3.3. *Constraints from Reionization*

If massive Population III stars led to an early reionization of the universe at $z \sim 17$, as may be required by the *WMAP* data (Kogut et al. 2003), we can obtain an estimate for the corresponding Population III SFR at $z_{\rm reion}$ and for the possible accompanying GRB rate as follows.

Population III stars with masses $\gtrsim$100 $M_\odot$ produce $\sim 10^{62}$ H-ionizing photons per solar mass over their $\sim 2\times10^6$ yr lifetime (e.g., Bromm et al. 2001b). We can then estimate that $\sim 3\times 10^5\ M_\odot$ in Population III stars are required to produce $\sim$5 ionizing photons for every hydrogen atom in a comoving cubic megaparsec. This number is sufficient to compensate for recombinations at the mean cosmic density. Assuming further that the burst of Population III star formation is spread over a fraction ϵ of the Hubble time at $z_{\rm reion} \sim 17$, $\Delta t_{\rm SF} \sim 4\times10^7(\epsilon/0.2)$ yr, the comoving Population III SFR able to reionize the universe at that redshift is ${\rm SFR_{reion}} \sim 7.5\times10^{-3}/(\epsilon/0.2)\ M_\odot\ {\rm yr^{-1}\ Mpc^{-3}}$. The extremely rapid growth of the collapsed fraction of baryons with redshift implies a value of $\epsilon \ll 1$; however, the minimum value of ϵ is $\sim$0.1 because even within a single dark matter halo, star formation cannot be synchronized to better than the dynamical time, which amounts to $\epsilon \sim 0.1$ for a virial density contrast of $\sim$200.

In Figure 2, we show the GRB rate that would correspond to ${\rm SFR_{reion}}$ for $\epsilon = 0.2$ when the constant Population I/II GRB efficiency factor is used, resulting in $\sim$0.1 GRBs per year. Under this conservative assumption, *Swift* is not expected to detect, within its expected 5 yr mission lifetime, any bursts connected to the Population III stars that were responsible for an early reionization of the universe. Again, the prospects for detection would be significantly improved if the Population III GRB efficiency is boosted due to the increased fraction of BH-forming progenitors.

4. SUMMARY AND CONCLUSIONS

Figure 2 leads to the robust expectation that $\sim$10% of all *Swift* bursts should originate at $z \gtrsim 5$. This prediction is based on the likely existence of Population I/II stars in galaxies that were already metal enriched at these high redshifts. Additional GRBs could be triggered by Population III stars, with a highly uncertain efficiency. Assuming that long-duration GRBs are produced by the collapsar mechanism, a Population III star with a close binary companion provides a plausible GRB progenitor. We have estimated the Population III GRB efficiency, reflecting the probability of forming sufficiently close and massive binary systems, to lie between zero (if tight Population III binaries do not exist) and $\sim$10 times the empirically inferred value for Population I/II (due to the increased fraction of BH-forming progenitors among Population III stars).

Recently, Gorosabel et al. (2004) and Natarajan et al. (2005) predicted the expected redshift distribution of long-duration GRBs, assuming they trace the cosmic star formation history, with various phenomenological prescriptions for the dependence on metallicity. In contrast to these studies, we isolate the zero-metallicity (Population III) stars and treat them as potential GRB progenitors based on a physical model.

It is of great importance to constrain the Population III star formation mode and in particular to determine down to which redshift it continues to be prominent. The extent of the Population III star formation will affect models of the initial stages of reionization (e.g., Wyithe & Loeb 2003a, 2003b; Ciardi et al. 2003; Sokasian et al. 2004; Yoshida et al. 2004; Alvarez et al. 2006) and metal enrichment (e.g., Mackey et al. 2003; Furlanetto & Loeb 2003, 2005; Scannapieco et al. 2003; Schaye et al. 2003; Simcoe et al. 2004) and will determine whether planned surveys will be able to effectively probe Population III stars (e.g., Scannapieco et al. 2005). The constraints on Population III star formation will also determine whether the first stars could have contributed a significant fraction to the cosmic near-IR background (e.g., Santos et al. 2002; Salvaterra & Ferrara 2003; Dwek et al. 2005; Kashlinsky 2005; Madau & Silk 2005; Fernandez & Komatsu 2006). If Population III binaries were common, *Swift* might be the first instrument to detect Population III stars from galaxies at redshifts $z \gtrsim 7$.

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