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 (Pop I and II) stars, and for predominantly massive (Pop III) stars. Based on these separate histories, we predict the GRB redshift distribution to be observed by the Swift mission. Regardless of whether Pop III progenitors are able to trigger GRBs, we find that a fraction $\sim 10\%$ of all bursts detected by Swift will originate at $z \gtrsim 5$. This baseline contribution is due to Pop 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 Pop III progenitors to the observable GRB rate. Pop III stars are viable progenitors for long-duration GRBs which 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 Pop III binaries to satisfy the conditions required by the collapsar mechanism could be enhanced significantly relative to Pop I/II binaries. If Pop III binaries are common, Swift will be the first observatory to probe Pop 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 (hereafter Pop III), formed out of metal-free gas at the earliest epoch of cosmic star formation. We construct separate star formation histories at high redshifts for normal (Pop I and II) stars, and for predominantly massive (Pop III) stars. Based on these separate histories, we predict the GRB redshift distribution to be observed by the Swift mission. Regardless of whether Pop III progenitors are able to trigger GRBs, we find that a fraction $\sim 10\%$ of all bursts detected by Swift will originate at $z \gtrsim 5$. This baseline contribution is due to Pop 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 Pop III progenitors to the observable GRB rate. Pop III stars are viable progenitors for long-duration GRBs which 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 Pop III binaries to satisfy the conditions required by the collapsar mechanism could be enhanced significantly relative to Pop I/II binaries. If Pop III binaries are common, Swift will be the first observatory to probe Pop III star formation at redshifts $z \gtrsim 7$.

Because of their high characteristic masses, Pop 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 Pop 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 Pop III contribution.

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The organization of the paper is as follows. In § 2 we describe our cosmic star formation model, in particular determining the Pop III mode at the highest redshifts. The resulting GRB redshift distribution is calculated in § 3, together with 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 Pop 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, Ferrara, & Rees 2001; Bromm et al. 2003; Furlanetto & Loeb 2003; Scannapieco, Schneider, & Ferrara 2003). Once a given region of the universe has been enriched beyond a critical metallicity, \( Z_{\mathrm{crit}} \sim 10^{-3.5} Z_\odot \), the mode of star formation is predicted to shift from high-mass Pop III stars to the lower-mass Pop I and II cases (e.g., Omukai 2000; Bromm et al. 2001a; Schneider et al. 2002; Bromm & Loeb 2003b; Mackey, Bromm, & Hernquist 2003; Schneider et al. 2003). The mass fraction of super-critical gas is rapidly growing toward lower redshift, and GRBs could be formed in the conventional way from metal-enriched Pop 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 Pop I/II and Pop III components.

2.1. Star Formation History

Our model for the total cosmic SFR closely follows that of Bromm & Loeb (2002), and we here 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, \( z_{\mathrm{reion}} \approx 7 \) and 17, where \( z_{\mathrm{reion}} \) corresponds to an ionization filling fraction by volume of \( \sim 50\% \). In each case, reionization is spread out over a range in redshifts, \( \Delta z/(1+z) \approx 1 \).

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 \( T_{\mathrm{vir}} \gtrsim 500 \) K, while atomic cooling dominates for halos with \( T_{\mathrm{vir}} \gtrsim 10^{3.9} \) K. Since H\(_2\) can be easily photo-dissociated by photons below the Lyman-limit, its significance in the cosmic star formation history is unclear (e.g. Bromm & Larson 2004 and references therein), and 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 one order of magnitude than the purely atomic cooling case discussed here.

![Cosmic comoving star formation rate (SFR) as a function of redshift.](image)

**Fig. 1.** Cosmic comoving star formation rate (SFR) in units of \( M_\odot \text{yr}^{-1} \text{Mpc}^{-3} \), as a function of redshift. We assume that cooling in primordial gas is due to atomic hydrogen only, and the star formation efficiency is \( \eta_\star = 10\% \). (a) Late reionization \( (z_{\mathrm{reion}} \approx 7) \). Solid line: Total comoving SFR. Dotted lines: Contribution to the total SFR from Pop I/II and Pop III for the case of weak chemical feedback. Dashed lines: Contribution to the total SFR from Pop I/II and Pop III for the case of strong chemical feedback. (b) Early reionization \( (z_{\mathrm{reion}} \approx 17) \). We adopt the same convention for the lines as in panel (a). In all cases, Pop III star formation is restricted to high redshifts, but extends over a significant range, \( \Delta z \sim 10 - 15 \).

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 photo-heated 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 \( (z_{\mathrm{reion}} \approx 7) \), we employ the prediction by Thoul & Weinberg (1996) that gas infall is com-
pletely suppressed in halos with circular velocities $v_c \lesssim 35 \text{ km s}^{-1}$. For the early reionization case ($z_{\text{reion}} \approx 17$), however, we use the recent work by Dijkstra et al. (2004), showing that the infall suppression due to photo-ionization 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 $v_c \lesssim 10 \text{ km s}^{-1}$.

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 $\eta_\ast \sim 10\%$, independent of redshift and regardless of whether the gas is primordial or pre-enriched. This efficiency yields roughly the correct fraction of $\Omega_M$ 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 one 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 Pop 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 which 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.

As can be seen in Figure 1, Pop 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 $\Delta z \sim 15$ for weak feedback. The Pop III histories are rather similar for both early and late reionization. The suppression of gas infall for the early reionization case (with $v_c \lesssim 10 \text{ km s}^{-1}$), 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 will predict the GRB redshift distribution for flux-limited surveys, distinguishing between the contributions from Pop I/II and Pop III star formation. In particular, we will 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 follows closely 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: $\psi_{\text{GRB}}(z) = \eta_{\text{GRB}} \times \psi_\ast(z)$, where $\psi_\ast(z)$ is the cosmic SFR, as calculated in §2. The efficiency factor, $\eta_{\text{GRB}}$, links the formation of redshifts to that of GRBs, and is in principle a function of redshift as well as the properties of the underlying stellar population. The stellar initial mass function (IMF) is predicted to differ fundamentally for Pop I/II and Pop 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 $\eta_{\text{GRB}}$ is constant with redshift for Pop I/II star formation, whereas Pop 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:

$$\psi_{\text{GRB}}(z) = \eta_{\text{GRB}} \psi_\ast(z) \int_{L_{\text{lim}}(z)}^{\infty} p(L) dL \ .$$

Here, $p(L)$ is the GRB LF with $L$ being the intrinsic, isotropic-equivalent photon luminosity (in units of photons s$^{-1}$). If $L_{\text{lim}}$ denotes the sensitivity threshold of a given instrument (in photons s$^{-1}$ cm$^{-2}$), then the minimum luminosity is:

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

where $d_L$ is the luminosity distance to a source at redshift $z$, and $\alpha$ 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 $f_{\text{lim}} = 0.04$ photons s$^{-1}$ cm$^{-2}$. Based on the first few months of actual observations by Swift, the sensitivity limit has recently been revised upward to $f_{\text{lim}} = 0.2$ photons s$^{-1}$ cm$^{-2}$, comparable to the older BATSE experiment (e.g., Berger et al. 2005). Using this revised flux limit, we predict that $\sim 10\%$ of all Swift GRBs will originate at $z \geq 5$.  

$^4$The weak and strong feedback cases correspond to $K_v^{1/3} = 1/3$ and 1 in equation (4) of Furlanetto & Loeb (2005).
where \( dN/d\eta \) 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 Pop I/II stars to \( \eta_{\text{GRB}} \approx 2 \times 10^{-9} \) GRBs \( \text{M}_\odot^{-1} \). 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 Pop 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 Pop III stars.

3.2. Population III Contribution

We begin by assuming that Pop III star formation gives rise to GRBs with the same (constant) efficiency as is empirically derived for Pop 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 Pop 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, on the other hand, that Swift will not detect any Pop III GRBs at all. Regardless of the uncertain contribution from Pop 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 Pop I/II progenitors that are known to produce GRBs, and those should exist at \( z \geq 5 \).

Adopting the same \( \eta_{\text{GRB}} \) for Pop III as for Pop 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 BH (see review by Piran 2004). 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 2005). For the collapsar to result in a GRB, additional requirements have to be met beyond the formation of a BH. We will discuss these next, and will then explore whether a subset of Pop 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):

(i) 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 \( \gtrsim 40 \text{M}_\odot \), or in a delayed fashion by fallback of the ejecta following a failed SN explosion for progenitor masses \( 25 \lesssim M_* \lesssim 40 \text{M}_\odot \) (e.g., Heger et al. 2003). The number of BH forming stars resulting from a given total stellar mass, here denoted by \( \eta_{\text{BH}} \), will depend on the stellar IMF which in turn is predicted to differ between the Pop I/II and Pop 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, \( M_{\text{low}} \) and \( M_{\text{up}} \) respectively. For Pop I/II stars, we take these to be: \( M_{\text{low}} = 0.1 \text{M}_\odot \) and...
The Pop 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 $M_{\text{up}} \sim 500M_\odot$ (Bromm & Loeb 2004), whereas for the lower limit, we consider two possibilities: $M_{\text{low}} \sim 30M_\odot$ (e.g., Tan & McKee 2004) and $\sim 100M_\odot$ (e.g., Abel et al. 2002; Bromm et al. 2002).

In general,

$$\eta_{\text{BH}} = \frac{\int_{M_{\text{up}}}^{M_{\text{BH}}} m^{-2.35} dm}{\int_{M_{\text{BH}}}^{M_{\text{low}}} m^{-1.35} dm}, \quad (4)$$

where $M_{\text{BH}} \simeq 25M_\odot$. For the Pop I/II case, this results in $\eta_{\text{BH}} \simeq 1/(700M_\odot)$. The Pop III lower mass limit exceeds the threshold for BH formation in either case, $M_{\text{low}} > M_{\text{BH}}$. Not every Pop III star, however, will leave a BH behind. In the narrow mass range of $\sim 140 - 260M_\odot$, Pop III stars are predicted to undergo a pair-instability supernova (PISN) explosion (e.g., Fryer, Woosley, & Heger 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 Pop III case, the expression results in $\eta_{\text{BH}} \simeq 1/(80M_\odot)$ for $M_{\text{low}} = 30M_\odot$, and $\eta_{\text{BH}} \simeq 1/(300M_\odot)$ for $M_{\text{low}} = 100M_\odot$. Thus, the BH formation efficiency is larger for Pop III compared to Pop I/II by up to one order of magnitude, depending on the lower mass limit.

(ii) 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 $r \sim ct \sim 50R_\odot$ before being slowed down to non-relativistic 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 $\sim 10^4R_\odot$ (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 will discuss both effects further.

(iii) 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 pre-collapse stellar core has a mass $M_c$, radius $R_c$, angular velocity $\omega_c$, 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 $M_{\text{BH}}$ is centrifugal support for material orbiting at the last-stable radius. This condition can be expressed as $j_c \gtrsim j_{\text{min}}$, with

$$j_{\text{min}} = \sqrt{6G M_{\text{BH}}/c} \simeq 3 \times 10^{16}\text{cm}^2\text{s}^{-1} \quad (e.g., \text{Podsiadlowski et al. 2004}).$$

Recent results obtained with sophisticated stellar evolution codes that include the effects of magnetic torques (e.g., Spruit 2002) have demonstrated the difficulty to identify progenitor systems for collapsar–driven GRBs that fulfill both conditions (ii) and (iii). 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 will explore this problem next, first for single-star progenitors, and then for binaries.

3.2.2. Single-star Progenitor

In massive Pop I/II stars, radiation driven winds can lead to vigorous mass loss, where the main source of opacity is provided by metal lines (e.g., Kudritzki & Puls 2000). Empirically, the existence of Wolf-Rayet (WR) stars proves that Pop I/II stars can indeed experience catastrophic mass loss, leading to the removal of the entire hydrogen—, 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 pre-collapse core, rendering the creation of a collapsar impossible.

For massive Pop III stars, radiatively driven winds are predicted to be unimportant (e.g., Kudritzki 2002; Krtička & Kubáč 2005). Alternatively, mass loss could occur as a result of stellar pulsations (through the $\epsilon$ mechanism). Simplified, linear calculations, however, indicate that this mechanism is not important below $\sim 500M_\odot$ (Baraffe, Heger, & Woosley 2001). There still remains an unexplored possibility that Pop III stars could experience significant mass loss driven by radiation pressure on He$^+$ ions, where 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 $Z > 10^{-4}Z_\odot$ at which point line-driven mass loss is predicted to set in (Kudritzki 2002; Marigo, Chiosi, & Kudritzki 2003). Recently, it has been suggested that WR 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 Pop 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, both for Pop 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 2005). Our main results, based on the cosmic Pop III SFR and the IMF-dependent BH fraction, however, holds 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, Brown, & Wijers 2002; Izzard, Ramirez-Ruiz, & Tout 2004). For Pop I/II, a binary pathway to a collapsar–driven GRB has already been suggested (e.g., Fryer et al. 1993). 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, 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: $\eta_{\text{CE}} \approx 1.0$ (Taam & Sandquist 2000). The frictional energy release during the in-spiral 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: $\omega_i \sim \omega_{\text{orb}}$. 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 $j_c \gtrsim j_{\text{min}}$ requirement.

### 3.2.4. GRB Formation Efficiency

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

It is currently not known whether Pop III stars can form binaries, and if so, what the corresponding binary fraction will be (e.g., Saigo, Matsumoto, & Umemura 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 where the collapsing gas had acquired a high degree of angular momentum, and where the collapse led to a disk-like configuration, pre-stellar 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 $\eta_{\text{min}} \lesssim 0.5$. More work, in particular involving improved numerical simulations, is required to constrain this crucial quantity further.

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

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

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

In summary, $\eta_{\text{GRB}}$ for Pop III stars is very uncertain, and could be zero in case that no Pop III binaries existed. On the other hand, one may argue that the binary properties for Pop III had been similar to Pop I/II, in cases where Pop 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 Pop III binary properties are similar to Pop I/II, we find a significant enhancement in $\eta_{\text{BH}}$ due to the difference in the IMF between the populations. We can then place an upper limit on the GRB rate from Pop III stars by multiplying the baseline rates in Figure 2 by a factor of $\sim 10$. This would result in Pop 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. 2005) 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 one order of magnitude, and such a Pop III contribution cannot be excluded with the current constraints from Swift.

### 3.3. Constraints from Reionization

If massive Pop 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 Pop III SFR at $\tau_{\text{reion}}$ and for the possible accompanying GRB rate, as follows.

Pop III stars with masses $\gtrsim 100M_\odot$ produce $\sim 10^{62}$ H-ionizing photons per solar mass over their $\sim 2 \times 10^6$ yr
lifetime (e.g., Bromm et al. 2001b). We can then estimate that $\sim 3 \times 10^3 M_\odot$ in Pop III stars are required to produce $\sim 5$ ionizing photons for every hydrogen atom in a comoving Mpc$^3$. This number is sufficient to compensate for recombinations at the mean cosmic density. Assuming further that the burst of Pop III star formation is spread over a fraction $\epsilon$ of the Hubble time at $\tau_{\text{reion}} \sim 17$, $\Delta t_{\text{SF}} \sim 4 \times 10^7 (\epsilon/0.2)$ yr, the comoving Pop III SFR able to reionize the universe at that redshift is: $SFR_{\text{reion}} \sim 7 \times 10^{-3}/(\epsilon/0.2) M_\odot$ yr$^{-1}$ Mpc$^{-3}$. The extremely rapid growth of the collapsed fraction of baryons with redshift implies a value of $\epsilon < 1$; however, the minimum value of $\epsilon$ is 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 which would correspond to $SFR_{\text{reion}}$ for $\epsilon = 0.2$ when the constant Pop 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 year mission lifetime, any bursts connected to the Pop III stars that were responsible for an early reionization of the universe. Again, the prospects for detection would be significantly improved if the Pop 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 Pop I/II stars in galaxies that were already metal–enriched at these high redshifts. Additional GRBs could be triggered by Pop III stars, with a highly uncertain efficiency. Assuming that long-duration GRBs are produced by the collapsar mechanism, a Pop III star with a close binary companion provides a plausible GRB progenitor. We have estimated the Pop III GRB efficiency, reflecting the probability of forming sufficiently close and massive binary systems, to lie between zero (if tight Pop III binaries do not exist) and $\sim 10$ times the empirically inferred value for Pop I/II (due to the increased fraction of BH–forming progenitors among Pop 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 difference from these studies, we isolate the zero-metallicity (Pop III) stars and treat them as potential GRB progenitors based on a physical model.

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

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