THE EXPECTED REDSHIFT DISTRIBUTION OF GAMMA-RAY BURSTS

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ABSTRACT

We predict the redshift distribution of Gamma-Ray Bursts (GRBs) assuming that they trace the cosmic star formation history. We find that a fraction $\gtrsim 50\%$ of all GRBs on the sky originate at a redshift $z \gtrsim 5$, even though the fraction of the total stellar mass formed by $z \sim 5$ is only $\sim 15\%$. These two fractions are significantly different because they involve different cosmological factors when integrating the star formation rate over redshift. Hence, deep observations of transient events, such as GRB afterglows or supernovae, provide an ideal strategy for probing the high-redshift universe. We caution, however, that existing or planned flux-limited instruments are likely to detect somewhat smaller fractions of high redshift bursts. For example, we estimate that the fraction of all bursts with redshifts $z \gtrsim 5$ is $\sim 10\%$ in the case of the BATSE instrument, and $\sim 25\%$ in the case of Swift. We also show that the intrinsic distribution of GRB durations is bimodal but significantly narrower and shifted towards shorter durations than the observed distribution.

Subject headings: Cosmology: theory — early universe — gamma rays: bursts

1. INTRODUCTION

Gamma-Ray bursts (GRBs) are the brightest electromagnetic explosions in the universe (for a recent review, see Piran 2000). Popular models for their central engine divide into two main classes: (i) the collapse of a massive star to a black hole (BH) (MacFadyen, Woosley, & Heger 2001, and references therein); (ii) the coalescence of a binary system involving a neutron star (NS) and a BH or a NS as a companion (e.g. Eichler et al. 1989; Janka et al. 1999). The observed association of long-duration GRBs with star forming regions (Djorgovski et al. 2001c, and references therein), and the possible supernova signatures in rapidly-decaying afterglows (Bloom et al. 1999; Kulkarni et al. 2000; Reichart 2001) favors the first class. Both classes of models associate GRB progenitors with compact objects (BH or NS) that are the end products in the evolution of massive stars. Hence, the GRB formation history is expected to follow the cosmic star formation history (Totani 1997, 1999; Wijers et al. 1998; Blain & Natarajan 2000) up to the highest redshifts ($z \sim 20$) at which the first generation of stars may have formed (Barkana & Loeb 2001). GRBs might therefore provide an ideal probe of cosmic star formation at all redshifts that in particular is unaffected by dust obscuration (e.g., Blain & Natarajan 2000; Porciani & Madau 2001). In fact, the top-heavy initial mass function (IMF) predicted for the first stars (Bromm, Coppi, & Larson 1999, 2002; Abel, Bryan, & Norman 2000, 2002; Nakamura & Umemura 2001) favors massive stars which are the likely source of GRB progenitors.

GRB afterglows provide a unique probe of the high redshift universe (Lamb & Reichart 2000; Ciardi & Loeb 2000). The bright, early optical-UV luminosity of a GRB afterglow is expected to outshine its host galaxy, even more so at high redshifts when the typical galaxies are less massive than their present-day counterparts (Barkana & Loeb 2001). The broad-band afterglow spectrum extends into the far UV and so the absorption features imprinted on it by the intervening intergalactic medium (IGM) can be used to infer the evolution of the neutral hydrogen fraction and the metal abundance of the IGM during the epoch of reionization. In difference from galaxies and quasars, which fade rapidly with increasing redshift due to the increase in their luminosity distance, GRB afterglows maintain an almost constant infrared flux with increasing redshift at a fixed time lag after the GRB trigger in the observer frame (Ciardi & Loeb 2000). This follows from the cosmological time-stretching of the afterglow transient (which is intrinsically brighter at earlier times) and from a favorable $K$-correction in the afterglow spectrum.

The Swift satellite$^1$, planned for launch in 2003, is expected to localize roughly one GRB per day. Sorting out the subset of all GRBs which originate at high redshifts ($z \gtrsim 5$) would be of particular interest. Observers may employ a simple strategy for this purpose. Photometric data from a small telescope should be used at first to identify those GRBs which possess a Ly$\alpha$ trough at a wavelength of $0.73\mu m (1+z)/6$ due to absorption by the IGM. Follow-up spectroscopy of those GRBs could then be done on a 10-m class telescope. In designing this observing strategy it is important to forecast which fraction of all GRBs originate from different redshifts. For example, it would be impractical to search for those very high redshifts which amount to a fraction smaller than $10^{-3}$ of all GRBs, because barely a single one of them would be found by Swift over several years of operation.

In this paper, we use existing observational and theoretical work on the cosmic star formation history to predict the fraction of all GRBs that are expected to originate at different redshifts. In order to keep our results general, we make predictions about all GRBs without reference to the detection threshold or redshift horizon of any particular instrument. To ascertain, however, what the BATSE and

$^1$See [http://swift.gsfc.nasa.gov](http://swift.gsfc.nasa.gov)
Swift instruments are expected to detect, we in addition estimate the redshift distributions for these flux-limited surveys.

In §2, we calculate the collapsed fraction of baryons as a function of redshift based on the Press-Schechter formalism, and infer the corresponding redshift distribution of GRBs. In §3 we use the inferred redshift distribution of GRBs to convert the observed distribution of GRB durations into the corresponding intrinsic distribution, under the simple assumption that its normalized form is redshift independent. Finally, we discuss the implications of our results in §4.

2. STRUCTURE FORMATION MODEL

2.1. Star Formation History

We adopt the popular view that the formation of cosmic structure has progressed hierarchically from small to large scales, according to a variant of the cold dark matter (CDM) model. Specifically, we assume a ΛCDM model with density parameters in matter Ω_m = 1 − Ω_Λ = 0.3 and in baryons Ω_B = 0.045; a Hubble constant of h = H_0/(100 km s^{-1} Mpc^{-1}) = 0.7, and a scale-invariant power spectrum of density fluctuations with an amplitude σ_8 = 0.9 on a scale of 8h^{-1}Mpc.

This assumed ionization history fits the semi-analytical calculation of Barkana & Loeb (2001) and is consistent with numerical simulations of reionization (Gnedin 2000, 2001; Razoumov et al. 2001) and the latest data on quasars in the redshift interval 5 ≤ z ≤ 6.3 (Becker et al. 2001; Djorgovski et al. 2001a; Fan et al. 2001). At high redshifts, z ≥ 20, the universe is predominantly neutral. Once the first luminous objects form, an increasing fraction of the IGM becomes ionized. At z_{reion} ≈ 7, the ionized phase in our model comprises a volume fraction of ∼ 50%, and reionization of the IGM is complete by z ≈ 5.6.

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 falls into a sufficiently deep CDM potential well, or equivalently, into a CDM halo more massive than a critical value. For the neutral medium, this minimum mass is set by the requirement for the gas to cool. Radiative cooling by molecular hydrogen (H_2) allows star formation in halos with a virial temperature T_{vir} ≥ 300 K, while atomic cooling dominates for halos with T_{vir} ≥ 10^{3.9} K. The corresponding minimum circular velocities are v_c ∼ 2.5 km s^{-1} and ∼ 12 km s^{-1}, respectively. 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. Haiman, Abel, & Rees 2000; Ricotti, Gnedin, & Shull 2001, and references therein), and so we show results with and without H_2 cooling. These two theoretical models are likely to provide conservative bounds for the true star formation history at z ≥ 5. The construction of more tightly constrained models has to await further advances in our understanding, both observational and theoretical, of star formation at the highest redshifts.

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 collapsing CDM halo be greater than the opposing pressure force on the gas. After reionization, the IGM is photo-heated to temperatures ≥ 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 (Thoul & Weinberg 1996). Expressing the Jeans mass as the equivalent halo circular velocity, we assume complete suppression for halos with v_c ≤ 35 km s^{-1}, no suppression for v_c ≥ 93 km s^{-1}, and a linear interpolation in between so that ∼ 50% suppression occurs at v_c ∼ 55 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 η_∗ ∼ 10%, independent of redshift and regardless of whether the gas is primordial or pre-enriched. This efficiency yields roughly the correct fraction of Ω_B found in stars in the present-day universe.

Figure 1 shows the resulting star formation histories. Our theoretical models agree well with observational esti-
mates of the cosmic star formation rate (SFR) at \( z \leq 2 \) (e.g., Blain et al. 1999). It is evident that there are two distinct epochs of cosmic star formation, one at \( z \sim 3 \), and a second one at \( z \sim 8 \) (or at even higher redshifts if H\(_2\) cooling is effective). Again, we emphasize that the true history of the cosmic SFR is likely to lie between the two curves in Figure 1, depending on how complete the destruction of H\(_2\) as a function of redshift is.

In deriving the redshift distribution of GRBs in the next section, we do not make any assumptions on the possible variation of the IMF for stars forming at different redshifts. Instead, we only assume that baryons are incorporated into stars, regardless of their specific properties, with the overall rate calculated in this section. Let us, however, briefly discuss the possible differences in star formation at high and low redshifts, based on recent theoretical work implying that star formation at high redshifts might have proceeded very differently from the present-day case, leading to stars with typical masses of \( M_* \gtrsim 100 M_\odot \) (Bromm et al. 1999, 2002; Abel et al. 2000, 2002; Nakamura & Umemura 2001). After the first stars have formed, the subsequent generation of stars forms out of gas that was already enriched with heavy elements. This enriched gas could have cooled more efficiently, and was able to reach lower temperatures. Star formation, then, is expected to result in a less top-heavy IMF. As shown by Bromm et al. (2001), the transition from a top-heavy to the more standard (Salpeter) IMF occurs when the mass fraction in metals exceeds a critical value of \( \sim 10^{-3} Z_\odot \). Gas with a metal abundance below this threshold is therefore still expected to form very massive stars. An IGM metal abundance of \( \sim 10^{-3} Z_\odot \) approximately corresponds to the production of enough ionizing stellar photons to reionize the universe. Star formation at \( z \gtrsim 7 \) might consequently have been dominated by very massive stars, whereas at lower redshifts, stars form with an IMF close to the Salpeter form.

### 2.2. Redshift Distribution of GRBs

Under the assumption that the formation of GRBs follows closely the cosmic star formation history with no cosmologically–significant time delay, we write for the number of GRB events per comoving volume per time:

\[
\psi_{\text{GRB}}(z) = \eta_{\text{GRB}} \times \psi_s(z),
\]

where \( \psi_s(z) \) is the stellar mass produced on average per comoving volume per time, as calculated in §2.1. The efficiency factor, \( \eta_{\text{GRB}} \), links the formation of stars to that of GRBs, and is in principle a function of redshift as well as the properties of the underlying stellar population. Massive stars of Population I differ fundamentally from those of Population III; moreover, it is at present not well understood how a massive Population III star may give rise to a GRB (see Fryer, Woosley, & Heger 2001; Schneider et al. 2001). Given the current state of uncertainty with regard to the central engine of GRBs (e.g., Piran 2000), we make the simplifying assumption that both populations of massive stars are connected to GRBs in a similar way, and take \( \eta_{\text{GRB}} \) to be independent of redshift. While this simplifying assumption follows from the lack of better information, our analysis provides a starting point for future improvements as soon as better observational constraints on high redshift GRB and star formation will become available.

If we now consider a time interval \( \Delta t_{\text{obs}} \) in the observer frame, the total number of GRBs, regardless of whether they are actually observed or missed, can be written as

\[
N(z) = \int_z^\infty \psi_{\text{GRB}}(z') \frac{\Delta t_{\text{obs}}}{(1 + z')} \frac{dV}{dz'},
\]

where \( dV/dz \) is the comoving volume element per unit redshift, given by

\[
\frac{dV}{dz} = \frac{4\pi c d_L^2}{1 + z} \left| \frac{dt}{dz} \right|.
\]

The luminosity distance, \( d_L \), to a source at redshift \( z \) is

\[
d_L = c(1 + z) \int_0^z \left( \frac{dz'}{1 + z'} \right) \left| \frac{dt}{dz'} \right| dz',
\]

with

\[
\left| \frac{dt}{dz} \right| = (1 + z) H_0 \sqrt{\Omega_m (1 + z)^3 + \Omega_\Lambda}.
\]

in a flat universe. The fraction of bursts that originate from a redshift of \( z \) or higher, \( f(z) = N(z)/N(0) \), is independent of constant parameters such as \( \Delta t_{\text{obs}} \), \( \eta_{\text{GRB}} \) or the beaming factor of the GRB emission. The integrand in equation (2) contains the differential comoving volume element, \( dV/dz \), as is appropriate for the calculation of an event rate. Since GRB events are communicated via photons, we integrate over the redshift-dependent comoving volume element along our past light cone. We observe these events over a fixed time window, \( \Delta t_{\text{obs}} \), which corresponds to \( \Delta t_{\text{obs}}/(1 + z) \) in the source frame. If, on the other hand, we were interested in determining the amount of stellar fossils that have accumulated over cosmic time in a local comoving volume (see below), we would have to simply integrate over cosmic time along our past worldline.
The fraction of all bursts that were detected by any given instrument depends on the instrument-specific flux sensitivity threshold and on the poorly-determined luminosity function (LF) of GRBs (see e.g., Schaefer, Deng, & Band 2001; Schmidt 2001; Norris 2002).

It is nevertheless instructive to ascertain what existing or planned instruments like BATSE and Swift are expected to find. To this extent, we modify the GRB event rate to have

$$\psi_{\text{GRB}}(z) = \eta_{\text{GRB}} \psi_\ast(z) \int_{L_{\text{lim}}(z)}^{\infty} p(L) dL. \quad (7)$$

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

$$L_{\text{lim}}(z) = 4\pi d_L^2 f_{\text{lim}}. \quad (8)$$

This expression is derived with a spectral index of $\alpha = 2$ for $L \propto \nu^{-\alpha}$ (Band et al. 1993). For definiteness, we assume a log-normal distribution function (e.g., Woods & Loeb 1995)

$$p(L) = \frac{e^{-\sigma^2/2}}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(\ln(L/L_0))^2}{2\sigma^2}\right] \frac{1}{L_0}, \quad (9)$$

where $\sigma$ and $L_0$ are the width and the average luminosity, respectively. Recently, Sethi & Bhargavi (2001) have shown that both the observed number count–flux relation as well as the existing afterglow redshift data are consistent with a log-normal LF for best-fit parameters (taking into account the effect of beaming): $\sigma = 2$ and $L_0 = 2 \times 10^{56}$ s$^{-1}$, and we adopt these values in the following analysis. To determine the expected redshift distribution as observed by BATSE and Swift, we use equation (2) together with the GRB rate given in equation (7). The flux thresholds are $f_{\text{lim}} = 0.2$ and 0.04 photons s$^{-1}$ cm$^{-2}$ for BATSE and Swift, respectively (Lamb & Reichart 2000, and references therein). In Figure 3, we show the same quantities as in Figure 2, but now comparing the distributions for BATSE and Swift with our theoretical prediction for atomic line cooling. It can be seen that in the case of BATSE a fraction of $f(z \geq 5) \gtrsim 10\%$ of all bursts originates from high redshifts, whereas the corresponding fraction for Swift is $f(z \geq 5) \gtrsim 25\%$. We emphasize again that these numbers are uncertain due to the poorly-known GRB LF. Figure 3 nicely demonstrates the asymptotic character of our theoretical prediction, pertaining to a future ‘ultimately-sensitive’ instrument. Indeed, using the LF above, we estimate that an instrument with a sensitivity of $\sim 50$ times better than Swift would be able to detect the full theoretically-possible sample of bursts from $z \geq 5$.

The detectability of $z \geq 5$ GRBs is also a crucial ingredient in estimating the fraction of all well-localized bursts that have no detectable optical afterglow, the so-called “dark GRBs”. Various authors have used the fraction of dark bursts in the currently observed sample of GRBs to constrain the amount of dust obscured star formation (e.g., Djorgovski et al. 2001b). The resulting fraction of dark GRBs estimated for different redshifts depends on the, presently unknown, level of incompleteness in the observed sample. In the context of our model, we predict...
that all GRB afterglows originating at $z \gtrsim 6$ are optically dark. The intervening, partially neutral IGM would efficiently absorb the rest-frame UV afterglow that would otherwise have been redshifted into the optical band (see also Fruchter 1999; Piro et al. 2002). These bursts might give rise to the recently discovered class of X-ray rich GRBs (e.g., Piro et al. 2002; see also Schneider et al. 2001) due to the redshifting of the source-frame $\gamma$-rays into the X-ray band.

3. BURST DURATIONS

The duration of a GRB reflects the characteristic timescale over which the central engine is active and is therefore a diagnostic of the GRB progenitor. The distribution of GRB durations has been determined by the BATSE instrument on board the Compton Gamma Ray Observatory (as summarized in Paciesas et al. 1999), and is observed to be bimodal with a population of short bursts centered on $T_{\text{obs}} \sim 0.3\,\text{s}$, and long bursts around $T_{\text{obs}} \sim 30\,\text{s}$ (Kouveliotou et al. 1993). For the definition of the burst duration, $T_{\text{obs}}$, we use the interval of time over which a GRB contains from 5 to 95% of its total observed $\gamma$-ray counts, also denoted as $T_{90}$ in the literature. Since bursts originate over a broad range of redshifts, the question arises as to what the intrinsic distribution of durations is like. For simplicity, we assume in this section that BATSE was capable of sampling the full redshift distribution of GRBs shown in Figure 2. This provides us with the maximum level of distortion that cosmological time dilation could have had on the observed distribution of burst durations. The true intrinsic distribution of durations for the BATSE-triggered bursts should lie in between the observed distribution and the intrinsic one calculated in this section.

The number of observed bursts in a given bin $i$, with an observed duration $T_{\text{obs},i}$ and a width $\Delta T_{\text{obs},i}$, can be written as

$$\Delta N_{\text{obs},i} = N_{\text{tot}} \Delta T_{\text{obs},i} \int_0^\infty \frac{dP}{dT}(T) \frac{1}{(1+z)} \frac{df}{dz}(z) dz,$$

(10)

where $N_{\text{tot}} = \sum_i \Delta N_{\text{obs},i}$ is the total number of bursts in the sample. We assume that the intrinsic distribution, $dP/dT$, is independent of redshift and satisfies $\int_0^\infty (dP/dT)dT = 1$ and $(dP/dT) \geq 0$. The intrinsic burst duration, $T$, is related to the observed one by the cosmological time dilation, $T = T_{\text{obs},i}/(1+z)$, and $(df/dz)$ is the GRB redshift distribution, as calculated in §2. We replace the integration in equation (10) by a summation, covering the range of intrinsic durations, $T$, with the same number of bins, $N_{\text{bin}} = 23$, as the observed histogram. The inversion problem is then uniquely defined. We carry out the deconvolution with the standard iterative Lucy method. This is a reliable technique, derived from Bayes' theorem, to solve a set of linear equations with additional constraints on the unknowns (Lucy 1974). The stability of the algorithm is improved by limiting the change in the unknowns in each iteration, and by smoothing over adjacent bins. To this extent, we use equation (11b) in Baugh & Elstathion (1993) with parameter values of $\beta = 0.8$ and $\epsilon = 0.9$. We have verified that the solutions are not very sensitive to the choice of these parameters.

The result of this inversion is shown in Figure 4, where we compare the derived intrinsic distribution to the observed one, $dP/dT_{\text{obs}}(T_{\text{obs},i}) = \Delta N_{\text{obs},i}/(N_{\text{tot}} \Delta T_{\text{obs},i})$. It is evident that the intrinsic durations are systematically shifted to shorter values due to the cosmological time dilation. The bimodality is preserved, with peaks that are narrower than the observed ones (note that the horizontal scale is logarithmic). The two star formation histories discussed in §2 lead to similar intrinsic distributions. The shift to shorter durations, however, is more pronounced in the case of star formation via H$_2$ cooling. The mean intrinsic durations characterising the first, short-duration, peak are $\sim 0.05\,\text{s}$ for cooling due to atomic hydrogen, and $\sim 0.03\,\text{s}$ for H$_2$ cooling. The corresponding numbers for the long-duration peak are $\sim 7\,\text{s}$ and $\sim 5\,\text{s}$, respectively. These differences in the mean durations are a direct consequence of the fact that GRBs originate on average at somewhat higher redshift if H$_2$ cooling is effective. Note that, statistically, the longest duration bursts, with $T_{\text{obs}} \gtrsim 1000\,\text{s}$, are expected to originate at high $z$, and this could be a successful selection strategy for observations targeting high–redshift GRBs. The shift to longer durations due to the cosmological time dilation could in part be compensated by the following subtle selection effect which we ignore in this paper. Sources at high $z$ will on average have lower fluxes, and observations with a given sensitivity threshold will therefore only detect the brightest portion of the total emission, thus systematically underestimating the true duration of the burst.

![Figure 4](image-url)
only ones with measured redshifts so far), one can easily derive the luminosity function from the intrinsic distribution of burst durations. The luminosity of a burst is then simply $\sim E/T$, and the resulting luminosity function is obtained by inverting the horizontal axis in Figure 4 and changing $T$ to $E/T$. The long-duration bursts would then narrowly cluster around a luminosity of $\sim 10^{50}\text{erg s}^{-1}$.

4. DISCUSSION

We have derived the redshift distribution of GRBs out to $z > 20$ under the assumption that the GRB event rate traces the cosmic star formation rate. We find that $\sim 50\%$ of all GRBs on the sky originate from a redshift of 5 or higher. On the other hand, the fraction of baryons that have been incorporated into stars by $z \sim 5$ is much smaller, comprising only $\sim 15\%$ of the stellar mass formed by today. The difference between the two fractions follows from the different cosmological factors in the redshift integrations for the statistics of transient events on the sky as compared to the census of fossil objects in the local universe. The favorable statistical bias towards high-redshift events on the sky is expected to apply also to Type II supernova explosions which are related to the formation of massive stars in a similar way as GRBs. Despite their diminishing with increasing redshift, high-redshift supernovae will be detectable with sufficiently sensitive telescopes such as the Next Generation Space Telescope (NGST; Miralda-Escudé & Rees 1997; Woods & Loeb 1998). In fact, our calculation implies that without any additional bias (such as redshift-dependent dust extinction) approximately half of all Type II supernovae detected by NGST will originate at $z > 5$. Deep observations of high-redshift GRBs and supernovae offer an ideal window into the earliest epoch of cosmic structure formation. The lengthening of the duration of these transients by a factor $(1+z)$ makes it easier for observers to monitor their lightcurves.

Different instruments may find GRBs up to different redshifts, depending on their detection sensitivity and the highly uncertain GRB luminosity function (Schafer et al. 2001; Schmidt 2001; Norris 2002). A trigger-unbiased way to infer the redshift evolution of the GRB event rate is to compare the number counts of GRBs with the same absolute (intrinsic) luminosity in different redshift bins. If future observations of this type were to determine a mean redshift for the GRB distribution significantly lower than the one predicted in this paper, then this would indicate either that GRB formation at high $z$ is substantially suppressed, or that GRBs originate from the coalescence of binaries with a time delay of a few Gyr before the formation of a massive star and the GRB event.

Recent observations indicate that a large fraction, $\sim 50\%$, of all well-localized GRBs have no associated optical afterglow, and are classified as “(optically) dark GRBs” (e.g., Piro et al. 2002). According to our model, a substantial fraction of these dark bursts could originate from $z > 6$. The intervening, partially neutral IGM would efficiently absorb the rest-frame UV afterglow that would otherwise have been redshifted into the optical band.

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