GAMMA-RAY BURSTS ARE PRODUCED PREDOMINATELY IN THE EARLY UNIVERSE

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ABSTRACT

It is known that some observed gamma-ray bursts (GRBs) are produced at cosmological distances and that the GRB production rate may follow the star formation rate. We model the BATSE-detected intensity distribution of long GRBs in order to determine their space density distribution and opening angle distribution. Our main results are: the lower and upper distance limits to the GRB production are \( z \approx 0.24 \) and \( >10 \), respectively; the GRB opening angle follows an exponential distribution and the mean opening angle is about 0.03 radians; and the peak luminosity appears to be a better standard candle than the total energy of a GRB.

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

1. INTRODUCTION

Recent results indicate that radiation from gamma-ray bursts (GRBs) may be constrained mostly to narrow beams (Waxman, Kulkarni, & Frail 1998; Fruchter et al. 1999; Woosley 2001), which suggests that GRBs may be standard candles at cosmological distances (Frail et al. 2001). Previous studies of the GRB space density distribution suggested that the GRB production rate might follow the observed star formation rate for low redshifts (Wijers et al. 1998) but may increase monotonically for very high redshifts (Schaefer, Deng, & Band 2001; Norris 2002); however, neither the lower nor upper redshift limits for GRB production could be determined reliably, because these studies are either limited by statistics or have to rely on some empirical relationships between some statistical properties of selected samples of GRBs. Because both the space density distribution and beaming effect play important roles for the observed GRB intensity distribution, here we make use of the Compton Gamma Ray Observatory (CGRO) BATSE GRB intensity distribution, which is the largest sample of GRBs collected so far, to determine directly the GRB space density and opening angle distribution.

2. MODELS FOR GRB INTENSITY DISTRIBUTION

For the GRB space density distribution, we assume the following model, with the cosmological parameters of \( \Omega = 1 \), \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \), and \( q_0 = 0.5 \), in order to compare with previous star formation rate measurements (Steidel et al. 1999):

\[
n(1+z) = \begin{cases} 
0, & \text{if} \quad z < z_0, \\
q_0(1+z)^{3.5}, & \text{if} \quad z_0 \leq z < z_{\text{break}}, \\
q_0(1+z_{\text{break}})^{3.5}, & \text{if} \quad z \geq z_{\text{break}}
\end{cases}
\]  

(1)

The functional form is taken from the measured star formation rate (Steidel et al. 1999), with \( z_0 > 0.2 \) and \( z_{\text{break}} \approx 1 \). Our main goal in this paper is to determine \( z_0 \) and \( z_{\text{break}} \) for GRBs from the observed GRB intensity distribution in order to find where in the universe GRBs are predominantly produced.

For the GRB opening angle distribution, we study three cases in which the GRB opening angle \( \theta \) follows a Gaussian, exponential, or power-law distribution. For a Gaussian distribution of \( \theta \), the probability that the opening angle equals a given \( \theta \) is

\[
P(\theta) = \frac{1}{\sqrt{2\pi \sigma}} e^{-[\theta-\theta_0]^2/(2\sigma^2)}.
\]

(2)

Assuming that the total energy \( E_0 \) is the same for every long GRB, i.e., they can be used as standard candles (Frail et al. 2001; Balazs et al. 2003), and that the opening angle \( \theta \) is very small, the probability that the observed fluence \( f \) is higher than a specified value \( F \) is then

\[
P(f \geq F) = P\left(\Omega \approx \frac{\pi}{4} \theta^2 \leq \frac{E_0(1+z)}{Fd_L^2}\right)
= \int_0^{4E_0(1+z)/Fd_L^2} \frac{\theta^2}{16\sqrt{2\pi}} \exp\left[-\frac{(\theta-\theta_0)^2}{2\sigma^2}\right]d\theta,
\]

(3)

where \( d_L \) is the luminosity distance. Thus the number of bursts detected is

\[
N = \int \frac{1}{4} \pi nd_L^2 d(d_L) \int_0^{4E_0(1+z)/Fd_L^2} \frac{\theta^2}{\sqrt{2\pi}} \exp\left[-\frac{(\theta-\theta_0)^2}{2\sigma^2}\right]d\theta.
\]

(4)

Similarly, for an exponential distribution with the parameter \( \lambda \),

\[
N = \int \frac{1}{4} \pi nd_L^2 d(d_L) \int_0^{4E_0(1+z)/Fd_L^2} \theta^2 \lambda e^{-\lambda \theta} d\theta,
\]

(5)
and for a power-law distribution with the parameter $t$,

$$N = \int \frac{1}{4} \pi n d^2 \theta \frac{dL}{d\theta} \int_{0}^{4L_0(1+z)/\pi F_d} \theta^{2-t} d\theta. \quad (6)$$

If we assume the peak luminosity of GRBs is a standard candle, we only need to replace $E_0$ and $F$ by the standard candle luminosity $L_0$ and the peak flux $P$ in equations (3), (4), (5), and (6), respectively. We number these slightly modified equations as (3)$'$, (4)$'$, (5)$'$, and (6)$'$, respectively; for brevity, we do not state these equations explicitly.

3. RESULTS

We apply equation (1) to fit the GRB space density distribution and equations (4), (4)$'$, (5), (5)$'$, and (6)$'$ for the GRB opening angle distribution to fit the observed GRB intensity distribution. We focus our study on long GRBs ($T_{90} > 2$ s; Kouveliotou et al. 1993), because, from the direct redshift measurements of the optical afterglows of some long GRBs, currently only long bursts are known to originate at cosmological distances. All long GRBs with peak flux values and detection probabilities above 5% in the GRB 4B+ Catalog (Paciesas et al. 1999, Hurley et al. 1999) are selected, resulting in 1727 GRBs as our sample. The fluence values of these GRBs are also taken directly from the catalog. For the peak flux distribution, the detection efficiency correction is done directly using the detection probability of each peak flux value given in the catalog. Because the fluence and peak flux do not have a good linear correlation, for each fluence range we average the detection probability of all GRBs included and then correct for the detection efficiency.

Our fitting results are shown in Table 1 and Figure 1. Because our fittings are done with the integral distributions, the numbers of GRBs in different bins are not completely independent. To address this problem, we carried out extensive bootstrap simulations. Taking the 1727 GRBs as the seed distribution, we randomly generated a large numbers of peak flux or fluence distributions and fitted the sampled distributions in the same way. The best values and errors of all parameters are then calculated from these fittings; the bootstrapped parameter values and errors are consistent with that listed in Table 1. We therefore believe the correction between the different points does not have any significant impact on our results. From the fitting results, we conclude:

1. For long GRBs, despite the different fitting residuals of the two standard candle models and the three assumed opening angle distributions, the cosmological parameters of GRBs inferred are strikingly similar, indicating the robustness of the GRB cosmological model.

2. The power-law distribution for the GRB opening angles cannot fit the data and is thus rejected.

![FIG. 1.—Comparison of different models with data. Top: Long GRBs with fluence as standard candle. Bottom: Long GRBs with peak luminosity as standard candle.](image)

| TABLE 1 | FITTING RESULTS FOR TOTAL ENERGY AND PEAK LUMINOSITY AS STANDARD CANDLES |
|---------|---|---|---|---|---|---|
|          | Gaussian | Exponential | Power-Law | Gaussian | Exponential | Power-Law |
| $\chi^2$ | 281.3/194 | 261.1/195 | 623.2/195 | 241/194 | 227.1/195 | 539.7/195 |
| Parameters | $\theta_0 = 0.028 \pm 0.007$ | $\lambda = 38.1 \pm 3.8$ | $t = 4.51 \pm 0.09$ | $\theta_0 = 0.031 \pm 0.008$ | $\lambda = 34.4 \pm 2.1$ | $t = 4.52 \pm 0.09$ |
| $\sigma$ | 0.050 ± 0.008 | 0.047 ± 0.01 | | | |
| $\sigma_{\text{break}}$ | 0.23 ± 0.07 | 0.23 ± 0.08 | 0.27 ± 0.11 | 0.23 ± 0.09 | 0.24 ± 0.07 | 0.29 ± 0.09 |
| $t_{\text{break}}$ | 7.7−∞ | 7.9−∞ | 7.2−∞ | 9.5−∞ | 9.8−∞ | 9.2−∞ |
| $E_0$ | 231 ± 51 | 215 ± 45 | 207 ± 44 | 273 ± 44 | 264 ± 49 | 257 ± 39 |
| $n_0$ | 0.69 ± 0.37 | 0.80 ± 0.41 | 0.72 ± 0.36 | 0.67 ± 0.32 | 0.64 ± 0.22 | 0.69 ± 0.30 |

Note: $\chi^2 = \chi^2 / \text{dof}$, $L_0$ is in units of $10^{51}$ ergs s$^{-1}$, and $n_0$ is in units of Gpc$^{-3}$ yr$^{-1}$. All errors quoted are for 68.3% confidence. For both cases, the exponential distribution of the opening angle offers the best fits; however, the residuals for the combination of peak luminosity as the standard candle and the exponential distribution is the only statistically acceptable one.
3. The Gaussian distributions for the GRB opening angles fit the data only marginally and are also rejected.

4. For both standard candle models, the exponential distribution for the GRB opening angles provides the best fit to the data.

5. The combination of the peak luminosity as standard candle and the exponential distribution for the GRB opening angles is the only one with a statistically acceptable fit to the data; we therefore accept this as the model for long GRBs. Under this model, the peak luminosity of a GRB is approximately $10^{53}$ erg s$^{-1}$ K$^{-8}$, the exponential constant of the opening angle distribution is $34 \pm 2$ radian$^{-1}$, the lower bound to the GRB redshift is $z_0 = 0.24 \pm 0.07$, and the upper break redshift is $z_{\text{break}} > 9.8$ (no lower limit to the break is detected because not enough sufficiently faint GRBs have been observed with BATSE).

4. DISCUSSION

First, we compare our study with previous studies of GRB cosmological models of the BATSE intensity distribution (Fenimore et al. 1993; Fenimore & Bloom 1995; Wickramasinghe et al. 1993; Wijers et al. 1998). All these studies concluded that the dimmest GRBs are at redshifts around unity, probably following the measured star formation rate, which peaks also at a redshift around unity (Steidel et al. 1999). The main differences between our approach and previous studies are the following:

1. We take the GRB opening angle distribution as part of the cosmological model. This is very important, since the observed GRB flux depends strongly on the opening angle, as well as on the redshift.

2. We separate the long and short GRBs into two different classes. Our conclusions are only applicable to long GRBs. For short GRBs, no conclusion can be drawn because of the limited statistical quality of the data.

3. One simplification of our study is that we did not make the energy spectral correction to the fluence or peak flux as a function of $z$ ($K$-correction); we just take the fluence or peak flux values as listed in the catalog. Technically this correction is not straightforward, because we can no longer uniquely convert the fluence or peak flux directly to redshift, since we believe that GRB radiation is beamed and that the opening angle follows a certain distribution. Therefore, the observed fluence or peak flux is due to both the redshift and the opening angle of the GRB. The good fit of the assumed simple cosmological model with only several free parameters indicates that this correction may not impact our conclusions significantly. In fact, since the energy spectra of GRBs in the BATSE band follows approximately a power law with an index of $-2$, the $K$-correction is not important.

Frail et al. (2001) suggested that the total energy of GRBs may be a constant, based on the opening angles of several GRBs determined from their afterglow light-curve break. Our result is not in major conflict with their suggestion but favors the peak luminosity as the standard candle. Perhaps the direction of the GRB beam is not completely stable, as indicated from observations of other relativistic jets and outflows from stellar mass and supermassive black holes; only when the beam is pointed directly at us can we observe the maximum flux from the GRB. However, it has been argued that for some GRBs, the lower limit of the total energy released is $10^{52}$ ergs, as determined from the redshifted X-ray emission lines (Ghisellini et al. 2002). However, the reality of the detection of the emission lines is still under debate, and an alternative interpretation of the detected emission lines also exists (Wang, Zhou, & You 2002).

The opening angles of some GRBs with afterglow detections have been determined previously from the GRB afterglow data (Frail et al. 2001; Bloom, Frail, & Kulkarni 2003); we call this the Frail distribution. In Figure 2, we compare the Frail distribution with the opening angle distributions determined from the observed GRB intensity distribution data, just as a sanity check. The power-law distribution agrees with the Frail distribution for large opening angles but fails to predict the absence of GRBs detected with opening angles smaller than 0.04 radian. No GRBs with opening angles narrower than 0.04 radian were directly observed, but the recent report on the polarization of GRB 021206 suggests that it is possible for some GRBs to have opening angles narrower than 0.01 radian (Coburn & Boggs 2003; Waxman 2003). The Gaussian distribution agrees with the peak of the Frail distribution reasonably well; however, this model does not predict enough

![Figure 2](image-url)
GRBs with opening angles greater than 0.2 radian. The exponential distribution is consistent with the Frail distribution for both standard candle models but slightly favors the peak luminosity standard candle model. It has been suggested that for the model in which the GRBs strictly follow the star formation rate, the most likely opening angle should be around 0.1 radian (Bloom et al. 2003). However, if the majority of faint GRBs originate at higher redshifts than that of the peak star formation rate as our model predicts, then a narrower average opening angle is required.

We therefore conclude that GRB opening angles follow an exponential distribution with a mean opening angle of $1/\bar{\theta} = 0.03$ radian and that the GRB space density follows a power law with an index of $-3.5$ between $z_0 = 0.24 \pm 0.07$ and $z_{\text{break}} > 10$. The general trend of the GRB space density distribution determined here as a function of $z$ is consistent with previous studies (Schaefer et al. 2001; Norris 2002); however, our result is statistically much more robust. In particular, $z_0$ is determined for the first time, and the lower limit to $z_{\text{break}}$ is constrained more strictly than before. Our result therefore demonstrates that GRBs are no longer produced frequently in the nearby, and present, universe at $z < 0.24 \pm 0.07$ and that GRBs are predominantly produced in the early universe at $z > 10$. Indeed, most GRBs with direct redshift measurements have redshifts $z > 0.3$ (Djorgovski et al. 2001), with the exceptions of GRB 980425 ($z = 0.0085$) and GRB 030329 ($z = 0.1687$), which may be associated with two peculiar but similar supernovae, SN 1998bw (van Paradijs 1999) and SN 2003dh (Stanek et al. 2003). It remains to be seen if these GRBs belong to a subset of GRBs, which are different from the majority of GRBs, which seem to be produced at much larger redshift.

It has been suggested that GRBs follow the star formation rate, because it is commonly believed that GRBs are produced in the final gravitational collapse of massive stars (Djorgovski et al. 2001; Paczynski 1998). The GRB space density determined here follows the measured star formation rate between $z \approx 0.24$ to 1. The determination of $z_0 = 0.24 \pm 0.07$ suggests that the massive stars capable of producing the majority of long GRBs are no longer formed frequently today. Future GRB experiments capable of measuring the redshift of many more GRBs and thus providing direct distance measurements of GRBs, such as the Swift mission to be launched in late 2003 (Gehrels 2000), will test this prediction firmly.

The monotonic increase of the GRB space density up to at least $z = 10$ suggests that the formation rate of massive stars capable of producing GRBs should peak at significantly higher $z$ than the measured star formation rate. This implies that the “dark ages” of the universe ended much earlier than $z \sim 4-5$ as previously believed, based on the measured space density distribution of high-redshift QSOs (Hook et al. 2002). Some previous work shows that some long GRBs should be at $z > 4$ (Choudhury & Srianand 2002; Bagoly et al. 2003) or even up to $z \approx 20$ (Meszaros & Meszaros 1996). A GRB recently detected by INTEGRAL, GRB 031203, was reported to be located at $z > 9$ (formally $z \geq 11$) (Bloom 2003), consistent with our model prediction. Therefore, GRBs may probe the epoch of reionization of the early universe (Lamb & Haiman 2003). Currently, the GRB intensity distribution data cannot constrain the exact upper limit of $z_{\text{break}}$ because not enough extremely faint GRBs have been observed. Future GRB experiments, such as the proposed “Next Generation GRB Mission” (Grindlay et al. 2003), would detect many more GRBs in the extremely early universe, which may determine the exact ending time of the “dark ages” of the universe, which will test the prediction of some numerical simulations (Abel, Bryan, & Norman 2002) that suggest that the first stars may have been formed at $z \sim 20$. GRBs may prove to be the most sensitive and ultimate probes into the early epoch of the universe when the first structures were formed.

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6 See http://grad40.as.utexas.edu/grblog.php?GCN=2468.

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