LONG GAMMA-RAY BURSTS TRACE THE STAR FORMATION HISTORY

Shlomo Dado and Arnon Dar
Physics Department, Technion, Haifa 32000, Israel
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ABSTRACT

We show that if the broad-line supernova explosions of Type Ic (SNeIc) produce the bulk of the observed long duration gamma-ray bursts (LGRBs), including high- and low-luminosity LGRBs and X-ray flashes, and if the LGRBs have the geometry assumed in the cannonball model of LGRBs, then their rate, measured by Swift, and their redshift distribution are consistent with the star formation rate (SFR) over the entire range of redshifts where the SFR has been measured with sufficient accuracy.

Key words: gamma-ray burst: general – supernovae: general

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1. INTRODUCTION

Core collapse supernovae (SNe) are produced by the explosive deaths of short-lived massive stars. Although very bright in optical light, ordinary core collapse SNe are not bright enough to be resolved in galaxies with redshift \( z > 1 \). As such, they can be used to trace the star formation history only up to redshifts \( z \sim 1 \).

Gamma-ray bursts (GRBs), the most luminous known electromagnetic events since the big bang, can be detected in MeV \( \gamma \)-rays up to very large redshifts, \( z \gg 10 \), with the current instruments on board satellites. Mounting photometric and spectroscopic evidence indicates that both long duration gamma-ray bursts (LGRBs) and low-luminosity X-ray flashes (XRFs) are produced by highly relativistic jets ejected in the Type Ic (SNeIc) core collapse SNe explosions of very massive stars, which occur at the end of their short lives.\(^1\) This suggests that the cosmic rate of LGRBs may trace the cosmic star formation rate (SFR; Wijers et al. 1998) back to very large redshifts beyond those accessible to optical measurements. However, the observed rates of LGRBs and XRFs do not follow the SFR. Unlike the SFR (in a comoving unit volume), which first increases with redshift, the observed LGRB rate (LGRBR) in the range \( z < 0.1 \) first decreases with increasing redshift, even after correcting for detector flux threshold (Guetta & Della Valle 2007), while at larger redshifts it increases faster than the SFR (Daigne et al. 2006; Le & Dermer 2007; Yuksel & Kistler 2007; Salvaterra & Chincarini 2007; Li 2008; Kistler et al. 2008; Salvaterra et al. 2009; Butler et al. 2010; Wanderman & Piran 2010; Virgili et al. 2011). The discrepancy at small \( z \) was interpreted as evidence that low-luminosity LGRBs and XRFs and ordinary LGRBs with much higher luminosity belong to physically distinct classes (Soderberg et al. 2004; Cobb et al. 2006; Liang et al. 2007; Soderberg et al. 2006; Pian et al. 2006; Amati et al. 2007; Chapman et al. 2007). The relative rate \( \Psi(z) = \text{LGRBR}/\text{SFR} \) was claimed to behave like \( \Psi(z) \propto (1 + z)^{\alpha} \) with \( \alpha \approx 0.5 \) in the range where both are well observed (e.g., Robertson & Ellis 2012; Wei et al. 2013).

The photometric (see, e.g., Dado et al. 2002; Zeh et al. 2004, and references therein) and spectroscopic evidence (see, e.g., Stanek et al. 2003; Hjorth et al. 2003; Wei et al. 2013; Cenko et al. 2013) that broad-line SNeIc produce both low-luminosity XRFs and high-luminosity LGRBs suggests that XRFs are ordinary LGRBs viewed far off axis (Dado et al. 2004) and that the different behavior of the LGRBR and SFR as a function of redshift, at both very low and very high redshifts, is due to observational selection effects. Indeed, the inferred evidence of differing behavior between the LGRBR and the SFR at both low and high redshifts involved the assumption that the beaming fraction \( f_b = (1 - \cos \theta) \) of detectable LGRBs is independent of \( z \). This assumption is valid in the standard conical fireball (FB) models of GRBs because \( \theta_b \), the opening angle of the conical jet that produces the observed GRB, is much larger than the relativistic beaming angle \( \theta_b = 1/\gamma \), which is associated with the jet bulk motion Lorentz factor \( \gamma \). Such a jet produces an afterglow with an achromatic temporal break at a time that is correlated to the prompt \( \gamma \)-ray emission properties, as well as closure relations between the temporal and spectral behaviors before and after the break (Rhoads 1997, 1999; Sari et al. 1999). However, all of these predictions proved to be at odds with the observed afterglow properties of most LGRBs (see, e.g., Dado & Dar 2013, and references therein).

In the cannonball (CB) model of GRBs (Dar & De Rújula 2004, and references therein), because of relativistic beaming, Doppler shift, and time aberration, the energy-flux \( F \), which comes from a highly relativistic CB (plasmoid) with bulk motion Lorentz factor \( \gamma \gg 1 \) and Doppler factor \( \delta \), decreases very rapidly, such as \( F \propto \gamma^2 \delta^4 \to \delta^{-8} \), when the viewing angle \( \theta \) relative to the CB’s direction of motion satisfies \( 1/\gamma^2 \ll \theta^2 \ll 1 \). This is because \( \delta = [1/\gamma(1 - \beta \cos \theta)] \approx 2\gamma/(1 + \gamma^2 \theta^2) \propto \theta^{-2} \) for \( \theta^2 \ll 1 \) and \( \gamma^2 \theta^2 \gg 1 \). As shown in Section 3, because of this rapid decline of the \( \gamma \)-ray flux, with viewing angle and the detector flux threshold, only a fraction \( f_{b0}(z) = 1 - \cos \theta_{\text{max}} \propto [D_L(z)]^{-1/2} \) of GRBs at redshift \( z \) with a luminosity above the detector threshold can be detected. In this paper, we show that such a decline in the beaming fraction, \( f_{b0}(z) \), of bipolar LGRBs and the observed SFR, which was compiled and standardized by Hopkins & Beacom (2006) and Reddy & Steidel (2009), reproduce the observed LGRBR quite well without invoking a relative evolution.

2. THE COSMIC RATE OF LGRBs

In the CB model, LGRBs are produced in SNeIc by highly relativistic bipolar jets of plasmoids (CBs), which are ejected...
during accretion episodes of fall-back material on the newly formed compact object (e.g., Dar & De Rújula 2004, and references therein). Because of relativistic beaming, such LGRBs can only be observed from directions near the jet. In SNeIc that produce observable GRBs, the highly relativistic jets interaction with the sub-relativistic SN ejecta results in much higher observed ejecta velocities toward the observer and consequently in ejecta absorption lines that are much broader than those usually observed during the photospheric phase of ordinary SNeIc that are not accompanied by an observable GRB. If most SNeIc produce GRBs that point away from Earth, as assumed in the CB model, then the observed cosmic rate of GRBs is the cosmic rate of SNeIc (SNIIcR) multiplied by the beaming factor

$$\frac{dN_{\text{GRB}}}{dz} \approx C f_b(z) \text{SNIIcR}(0) \frac{\text{SFR}(z)}{\text{SFR}(0)} \frac{dV_c(z)}{dz} \frac{1}{1+z},$$

(1)

where $C$ is the fraction of the sky covered by the GRB detector and $dV_c(z)/dz$ is the comoving volume at redshift $z$. In a standard ΛCDM cosmology,

$$\frac{dV_c(z)}{dz} = \frac{c}{H_0} \frac{4 \pi [D_L(z)]^2}{\sqrt{(1+z)^3 \Omega_M + \Omega_{\Lambda}}},$$

(2)

where $H_0$ is the current Hubble constant, $\Omega_M$ and $\Omega_{\Lambda}$ are, respectively, the current density of ordinary energy and dark energy, in critical energy-density units, and $D_L(z)$ is the comoving distance at redshift $z$, which satisfies

$$D_L(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{(1+z')^3 \Omega_M + \Omega_{\Lambda}}.$$  

(3)

3. THE BEAMING FACTOR IN THE CB MODEL

The CB model's predictions and extensive comparisons with GRB observations have been described in great detail in many publications (see, e.g., Dar & De Rújula 2004 for a review; Dado et al. 2009a, 2009b for comparisons with observations). For readers unfamiliar with the CB model, a short description is enclosed in the Appendix.

In the CB model, the Doppler shift, relativistic beaming, and time aberration of the observed radiation reveal the strong dependence of the observed properties of GRBs on the bulk motion Lorentz and Doppler factors of the CBs (e.g., Dar & De Rújula 2000, 2004; Dado & Dar 2013, and references therein). In particular, the peak luminosity of LGRBs satisfies $L_p = L_0 \gamma^2 \delta^4$. Because of the detector energy-flux threshold $F_{\text{thr}}$, LGRBs at redshift $z$ are detectable only when

$$L_p = L_0 \gamma^2 \delta^4 > 4 \pi [D_L(z)]^2 F_{\text{thr}},$$

(4)

where $D_L(z) = (1+z) D_c$ is the luminosity distance to redshift $z$. Figure 1 presents the distribution of $L_p(z)$ of Swift LGRBs as a function of redshift for all Swift LGRBs, which were detected before 2013 November 15 and are listed in the Greiner catalog of GRBs and whose $L_p$ was measured with Konus-Wind and/or Fermi GBM and reported in the GCN archive.\(^2\) The lower limit behaviors expected from Equation (4) and the upper limit max $L_p(z)$ = const for the LGRB population with no redshift evolution are also shown by lines.

\(^2\) http://www.mpe.mpg.de/~jcg/grbgen.html

\(^3\) http://gcn.gsfc.nasa.gov/gcn_main.html

![Figure 1. Distribution of the isotropic equivalent peak gamma-ray luminosity, $L_p(z)$, as a function of redshift of Swift LGRBs that were detected before 2013 November 15 and are listed in the Greiner catalog of GRBs and whose $L_p$ was measured with Konus-Wind and/or Fermi GBM and reported in the GCN archive. Also shown are the best fit lower limit line $L_p(z)$ $\times$ $D_L(z)^2$ and the upper limit line max $L_p$ = const line expected in the CB model of LGRBs. (A color version of this figure is available in the online journal.)](image-url)
eruptions sometime before its SNIIc explosion. If \( z_{\text{m}} \) is the redshift of the LGRB with the lowest measured \( E_p' \), then

\[
E_p' = 4.5 \text{ keV}, \quad \text{the lowest } E_p' \text{ value measured for a } Swift \text{ GRB. In terms of these values, Equation (5) can be written as}
\[
\eta(z) = 1 - \cos \theta_{\text{max}} \approx 6.6 \times 10^{-4} \left( \frac{D_L(z)}{D_L(0.0331)} \right)^{-1/2}.
\]  

This beaming factor is shown in Figure 5 as an upper bound line to the \( z \)-distribution of the 1 \( \cos \theta \) values extracted from the CB model relation, 1 \( \cos \theta \approx 1/(\gamma \delta) \) = \( \epsilon_g / E_p' \). The 134 Swift LGRBs and XRFs that were detected before 2013 November 15 have a known redshift listed in the Greiner catalog of GRBs and an \( E_p' \) value measured with Konus-Wind and/or Fermi GBM and reported in the GCN archive.\(^3\)

Note that for \( z < 0.1 \), where \( D_L(z) \approx D_c \approx c z / H_0 \), Equation (1) can be integrated analytically over time and redshifted to yield the approximate behavior,

\[
N(<z) \approx C \text{ SNIIcR}(0) T \frac{\epsilon_g}{\min E_p'} \frac{8 \pi}{5} \left( \frac{c}{H_0} \right)^3 \frac{z_{\text{m}}^{1/2}}{z^{5/2}},
\]  

where \( T \) is the total observation time.

4. COMPARISON WITH OBSERVATIONS

**Priors.** In order to compare theory and observations, we have adopted:

1. The current best values of the cosmological parameters from the Planck data (Ade et al. 2013): a Hubble constant \( H_0 = 67.3 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.315 \) and \( \Omega_\Lambda = 0.685 \).
2. The local rate of SNeIc, \( 0.065 \pm 0.032 \) SNe, estimated by Arbutina (2007), where SNeI = SN per \( 10^{10} L_\odot \) per century for the above value of \( H_0 \). For a local luminosity density of \( 1.4 \times 10^8 L_\odot \text{ Mpc}^{-3} \), it yields SNIIcR(0) \( \approx (9.0 \pm 4.5) \times 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1} \).
3. The SFR that was compiled and standardized by Hopkins & Beacom (2006) and by Reddy & Steidel (2009) from optical measurements. This standardized SFR is well approximated by a log-normal distribution,

$$\text{SFR}(z) \approx 0.25 e^{-[\ln((1+z)/3.16)]^2/0.524} \, M_\odot \, \text{Mpc}^{-3} \, \text{yr}^{-1}.$$  \hfill (9)

4. The probability, $\langle P(z) \rangle$ $\approx 262/749 = 0.35$, of a Swift LGRB to have a measured redshift (from emission lines of the LGRB host galaxy and from the absorption lines or photometry of its optical afterglow). Out of the 749 Swift LGRBs detected through 2013 November 15, only about 50% have a detected optical afterglow, despite rapid optical follow up, and only 262 have a measured redshift. Most of the “missing redshifts” are probably due to dust extinction, the limiting sensitivity of the telescopes, and the time it takes to acquire spectroscopic/photometric redshifts (e.g., Coward et al. 2013). From the relative number of LGRB redshift measurements by the three methods as a function of $z$ reported in the GCN catalog,$^3$ we have estimated that $P(z) \approx 0.684 e^{-z^2/0.5} + 0.316$. However, the use of this rough estimate instead of $P(z) = \langle P(z) \rangle$ has a negligible effect on our results,except for $z \lesssim 0.1$ (see below).

Tests of the SFR-LGRBR connection. Because of the different sensitivities and sky coverage of different GRB missions, we have limited our comparison to the 262 LGRBs and XRFs with known redshift that were detected by Swift before 2013 November 15, which are listed in the Greiner catalog of GRBs. For this choice:

The daily rate of LGRBs obtained by integrating Equation (1) over redshift, using Equations (2), (3), and (7), and the priors (a)–(c), is LGRBR $\approx 2.1 \pm 1.5 \, \text{day}^{-1}$ of observable LGRBs (high-luminosity GRBs + low-luminosity GRBs + XRFs) for a full sky coverage ($C = 1$). The 749 LGRBs detected by Swift before 2013 November 15 with a sky coverage of $C \approx 1.4/4 \pi = 0.11$ (Salvaterra & Chincarini 2007), yield $\approx 2.07 \, \text{day}^{-1}$ Swift-like LGRBs over the entire sky, in agreement with that obtained from Equation (1).

The redshift distribution of Swift LGRBs with known redshift is compared in Figure 6 to that predicted by Equations (1)–(3), and (7) with the priors (a)–(d). The predicted mean redshift, $\langle z \rangle = 2.08$, is consistent with $\langle z \rangle = 2.12$, obtained from the reported redshifts of the 262 Swift LGRBs with known redshift, which are listed in the Greiner GRB catalog. The agreement between the expected and the observed distribution is quite good ($\chi^2/\text{dof} = 25.5/26 = 0.98$, significance level 49%, assuming Poisson statistics, i.e., $\sigma_i = \sqrt{N_i}$, where $N_i$ is the observed number of LGRBs in bin $i$). The bins 21–30 and 31–50 were converted to two bins $5 < z < 7$ and $7 < z < 10$, respectively, in order to have $N_i \geq 5$. Similar agreement ($\chi^2/\text{dof} = 48.88/49 = 1.00$, significance level 48%) was obtained when all of the 50 $z$ bins of width $\Delta z = 0.2$ shown in Figure 6 were included in the $\chi^2/\text{dof}$ calculation, but the standard deviation errors, $\sigma_i = \sqrt{N_i}$, were estimated from the predicted value of $N_i$. Similar agreement ($\chi^2/\text{dof} = 7.56/7 = 1.08$, with a significance level of 37%, and $\chi^2/\text{dof} = 5.02/5 = 1.00$ with a significance level of 41%, respectively) were obtained for the TOUGH (56 Swift LGRBs; Hjorth et al. 2012) and BAT6 (52 Swift LGRBs; Salvaterra et al. 2012) samples when they were compared to the CB model predicted distribution.

Figure 6, however, indicates an $\sim 8$ LGRBs deficiency of Swift LGRBs with measured redshift in the bin $1.8 \leq z \leq 2.0$, in the so-called GRB redshift desert, which is believed to be due to an observational bias rather than a real deficiency (Coward et al. 2013). Indeed, the TOUGH, and in particular the BAT6 sample of bright Swift LGRBs (Salvaterra et al. 2012), have a redshift distribution where the “GRB desert” is almost completely filled. Adding eight “missing LGRBs” to the (1.8 < z < 2.0) bin of the Swift distribution of 262 LGRBs improves the good agreement reported above to a remarkable agreement between the differential distribution predicted by the CB model and the observed distribution ($\chi^2/\text{dof} = 15.8/24 = 0.66$, significance level 90%).
Swift NLGRB(<z)

Figure 7. Comparison between the cumulative distribution \( N(<z) \) of the 262 Swift LGRBs with known redshift that were detected before 2013 November 15 and the distribution expected in the CB model of LGRBs produced in SNeIc with a rate that traces the SFR.

(A color version of this figure is available in the online journal.)

Figure 8. Comparison between the cumulative distribution function, \( N(<z) \), of the 262 LGRBs with known redshift (histogram) that were detected by Swift before 2013 November 15 after adding eight “missing” LGRBs with \( 1.8 < z < 2.0 \) and the corresponding \( N(<z) \) expected in the CB model (left curve) for LGRBs produced in SNeIc whose rate traces the SFR. Also shown are the distributions expected in the FB model with a relative evolution (\( \alpha = 0.5, \) right curve) and with no evolution (\( \alpha = 0, \) middle curve).

(A color version of this figure is available in the online journal.)

The cumulative distributions, \( N(<z) \), of the 262 and 270 (262+8 missing) Swift LGRBs with known redshift, which were detected before 2013 November 15, and the cumulative distributions predicted by the CB model (using Equations (1)–(3), and (7) with the priors (a)–(d)) are compared in Figures 7 and 8, respectively. Also shown in Figure 8 are the expected distributions in the standard FB model with a relative evolution (\( \alpha = 0.5, \) right curve) and with no evolution (\( \alpha = 0, \) middle curve).

The observed rate of low-luminosity LGRBs and XRFs was compared in Figure 9 with that predicted by Equation (7), assuming that the probability of obtaining the redshift of the host galaxies of very nearby LGRBs is \( P(z) \approx 1 \) rather than the mean value \( P(z) \approx 0.35 \) for the entire \( 0 < z < 10 \) range. Also, because of the limited statistics, the true \( f_0(z) \) for Swift LGRBs may lie somewhat above the upper limit shown in Figure 5. Indeed, the lowest reported \( E_p' \) value of LGRB was but with (a best fit obtained by Robertson & Ellis (2012) and by Wei et al. (2013) to their selected samples of 112 and 86 bright Swift LGRBs, respectively, in the range \( z \leq 4 \). As can be seen by simple inspection of Figures 7 and 8, the agreement between the observed and the CB model distributions of the complete sample of Swift LGRBs with known redshift (0.0331 \( \leq z \leq 9.2 \)) is very good and becomes remarkable once the “eight missing GRBs” are added to the \( (1.8 < z < 2.0) \) bin. \( ^4 \)

The cumulative distribution shown in Figure 8 allows alternative formal tests of goodness of fit, such as the Kolmogorov–Smirnov (K-S) and Anderson–Darling statistical tests. Such tests also yield very high significance levels for the agreement between the observed cumulative distribution function (CDF) and the CB model CDF and rejection of the FB model CDFs with \( \alpha \geq 0 \) relative evolution. For instance, the K-S statistic of the CB model fit, \( D_{\text{max}} = 0.0436 \) for \( n = 262 \) yields a significance level >90%, while models with \( f_b = \text{const} \) with \( \alpha = 0, 0.5 \) and 1.5 yield \( D_{\text{max}} = 0.151, 0.222, \) and 0.382, respectively, with a significance level \( \ll 1\% \).

The observed distribution of LGRBs \( < 0.1 \) was compared in Figure 5 with that predicted by Equation (7), assuming that the mean value \( P(z) \approx 0.35 \) for the entire \( 0 < z < 10 \) range. Also, because of the limited statistics, the true \( f_0(z) \) for Swift LGRBs may lie somewhat above the upper limit shown in Figure 5. Indeed, the lowest reported \( E_p' \) value of LGRB was

\[ ^4 \text{The sum of independent variables with a Poisson distribution is also a Poisson distribution with a mean and a variance equal to the sum of means and variances of the independent variables. Hence, the standard deviation error of } N(<z) \text{ is } \sqrt{N(<z)}. \text{ Moreover, the significance level of a } \chi^2 \text{ goodness of fit to the binned differential distribution is also the significance level of agreement between the corresponding binned theoretical and measured cumulative distribution functions (CDFs).} \]
\[ E'_\gamma = 3.37 \pm 1.79 \text{ keV} \text{ for XRF020903 at } z = 0.25, \text{ measured with the HETE satellite (Amati et al. 2002).} \]

For the Lorentz factor $\gamma$, estimated from these values and $P(z) = 1$, Equation (6) yields 0.33, 1.4, 3, and 3.9 expected detections ($\pm 70\%$ estimated error) of LGRBs+XRFs with redshift smaller than 0.0331, 0.059, 0.080, and 0.089, respectively, which are the redshifts of XRF060218 (Mirabal & Halpern 2006), GRB100316D (Vergani et al. 2010), XRF051109B (Perley et al. 2006), and GRB060505 (Ofek et al. 2007), the lowest $z$ LGRBs that were detected by Swift during $T \approx 9 \text{ yr}$ of observations (see the Greiner GRB catalog\(^5\)). The above predicted values are in agreement with the corresponding values 0, 1, 2, and 3 of the observed cumulative distribution. Moreover, since the launch of the BeppoSAX in 1996, only one GRB (980425 at $z = 0.0085$) was detected by the $\gamma$-ray satellites at a redshift smaller than 0.0331 during a combined effective observation time of roughly $T \approx 17 \text{ Swift observation years}$, compared to 0.66 $\pm$ 0.46 expected in the CB model.

5. DISCUSSION AND CONCLUSIONS

Star formation at redshifts $z > 6$ may have made an important contribution to the reionization of the universe, to its optical depth, the cosmic background radiations, and its metallicity at high redshifts. However, direct measurements of the SFR at redshifts $z \gtrsim 6$ and their correct interpretation are quite challenging (for a review, see, e.g., Robertson et al. 2010). LGRBs, which are produced in the SNeIc explosions of massive stars, whose optical afterglows are visible at redshifts that substantially exceed those where the direct measurements of the SFR are still possible, offer the possibility to extend the SFR "measurements" to redshifts that are far beyond those of the direct measurements.

The measured rate of LGRBs as a function of redshift, however, was claimed to differ significantly from the observed SFR, both at low and high redshifts (the discrepancy claimed at low redshift was a factor of $\sim 100$). In this paper, we show that the use of the CB model beaming fraction brings the observed GRB rate and the SFR in the $z$ range into remarkable agreement where both were accurately measured.

The discrepancy claimed at low redshift was explained by assuming that LGRBs with low isotropic luminosities belong to a class that is different from that of LGRBs with high isotropic equivalent luminosities. However, this is at odds with the observations that both the low-luminosity and the high-luminosity LGRBs are produced by similar broad-line SNeIc. Moreover, this assumption does not explain why the observed rate, as a function of redshift of low-luminosity LGRBs produced by SNeIc, does not follow that of the SFR at $0 < z < 0.1$.

In the range $0.1 \leq z \leq 4$, the LGRBR was claimed to have a more rapid evolution relative to the SFR, which can be well parameterized by $(1 + z)^{0.5}$. However, such a relative evolution (assuming a $z$-independent beaming factor), which was shown to fit well selected samples of bright Swift LGRBs with a known redshift in the range $z < 4$ (Robertson & Ellis 2012; Wei et al. 2013), fails to describe the complete distribution of the Swift LGRBs with known redshift that currently extend over $0.0331 \leq z \leq 9.2$. In fact, FB models with a $z$-independent beaming factor and $\alpha \geq 0$ overpredict the high $z$ SFR inferred from the abundance of UV-selected galaxies (Robertson & Ellis 2012, and references therein).

In this paper, however, we have shown that the above discrepancies may have been the result of assuming a redshift-independent beaming factor of LGRBs, which was adopted from the underlying current geometry of the standard conical FB model of LGRBs. Once the assumed conical geometry of LGRBs is replaced by the geometry adopted in the CB model of GRBs, the beaming factor of LGRBs becomes $z$-dependent as a result of the detection threshold of GRBs. We have shown that this plus the assumption that all SN/Ic produce LGRBs, most of which are beamed away from Earth, yields a theoretical rate of LGRBs that correctly reproduces (1) the full sky rate of cosmic LGRBs ($\approx 2.1 \text{ day}^{-1}$) above the Swift detection threshold, (2) the observed distribution of Swift LGRBs with known redshift as a function of the redshift and consequently (3) the observed mean redshift $\langle z \rangle \approx 2.12$ of Swift LGRBs with known $z$, and (4) the cumulative distribution $N(< z)$ of Swift LGRBs as a function of $z$ between their lowest and highest observed redshifts.

We conclude that LGRBs seem to trace the SFR as a function of redshift up to at least $z \approx 6$, that most SNeIc probably produce LGRBs beamed away from Earth, and that the high-luminosity LGRBs and the low-luminosity LGRBs and XRFs seem to belong to the same class of SN/Ic-GRBs. The observed differences between them are produced by the strong dependence of the observed LGRB properties on detector threshold, their Lorentz factor, and viewing angle, which are all well described by the CB model of GRBs.

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APPENDIX

OUTLINE OF THE CB MODEL OF LGRBS

In the CB model of GRBs (Dado et al. 2002; Dar & De Rújula 2004; Dado et al. 2009a, 2009b), LGRBs and their afterglows are produced by the interaction of bipolar jets of highly relativistic ($\gamma \gg 1$) plasmosoids (CBs) of ordinary matter with the radiation and matter along their trajectory (Shaviv & Dar 1995; Dar 1998). Such jetted CBs are presumably ejected in accretion episodes on the newly formed compact stellar object in core-collapse SN explosions (Dar et al. 1992; Dar & Plaga 1999; Dar & De Rújula 2000). It is hypothesized that an accretion disk, or a torus, is produced around the newly formed compact object, either by stellar material originally close to the surface of the imploding core and left behind by the explosion-generating outgoing shock, or by more distant stellar matter falling back after its passage (Dar & De Rújula 2000, 2004). As observed in microquasars, each time part of the accretion disk falls abruptly onto the compact object, two CBs made of ordinary-matter plasma are emitted in opposite directions along the rotation axis from where matter has already fallen back onto the compact object due to the lack of rotational support. The prompt X-ray pulses and early-time X-ray flares are dominated by ICS of glory photons—a light halo surrounding the progenitor star that was formed by stellar light scattered from the pre-SN ejecta/windblown from the progenitor star—by the CBs electrons. The ICS is overtaken by synchrotron radiation when the CB enters the pre-SN wind/ejecta of the progenitor star.

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