Reconciliation Of The Disparate Gamma-Ray Burst Catalogs In The Context Of A Cosmological Source Distribution

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Abstract

It is well known that Gamma-ray Burst spectra often display a break at energies $\lesssim 400$ keV, with some exceptions extending to several MeV. Modeling of a cosmological source population is thus non-trivial when comparing the catalogs from instruments with different energy windows since this spectral structure is redshifted across the trigger channels at varying levels of sensitivity. We here include this important effect in an attempt to reconcile all the available data sets and show that a model in which bursts have a “standard” spectral break at 300 keV and occur in a population uniformly distributed in a $q_0 = 1/2$ universe with no evolution can account very well for the combined set of observations. We show that the source population cannot be truncated at a minimum redshift $z_{\text{min}}$ beyond $\sim 0.1$, and suggest that a simple follow-on instrument to BATSE, with the same trigger window, no directionality and 18 times better sensitivity might be able to distinguish between a $q_0 = 0.1$ and a $q_0 = 0.5$ universe in 3 years of full sky coverage, provided the source population has no luminosity evolution.

Subject headings: cosmology: observations – cosmology: theory – galaxies: clustering – galaxies: evolution – gamma rays: bursts – pulsars
1. Introduction

Observations with the Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory (CGRO) reveal an isotropic distribution of Gamma-ray Bursts (GRBs) which nonetheless appears to be radially truncated in the context of a Euclidean geometry (Meegan et al. 1992). This seems to rule out nearby (i.e. Galactic disk) single population models, and has led to renewed speculation that GRBs originate at large redshifts (Usov & Chibisov 1975). Recently, the cosmological hypothesis has been revisited by, e.g. Mao & Paczyński (1992), Piran (1992), and Dermer (1992), who considered the relation between the geometrical distribution of GRB sources and the statistics of the observed bursts under the simplifying assumption that all the bursts are standard candles with identical power-law spectra. In particular, Mao & Paczyński (1992) showed that the simplest cosmological model (i.e., a flat universe with \( \Omega = 1 \) and a cosmological constant \( \Lambda = 0 \)) corresponds reasonably well with the intensity distribution of weak and strong bursts observed with BATSE and PVO (Epstein & Hurley 1988).

How these bursts might be produced is not at all clear, though several plausible physical scenarios continue to evolve. Non-catastrophic processes require focusing of the emitted energy, such as would occur in sheared Alfvén wave dissipation near the polar cap of highly-magnetized neutron stars which produce streams of relativistic particles that are beamed by the underlying magnetospheric structure (Melia & Fatuzzo 1992). In this case, the GRB spectrum results from the Compton upscattering of the corresponding radio pulsar radiation, which is often characterized by a spectral turnover at \( \sim 1 \) GHz. This feature should therefore manifest itself as a break at gamma-ray energies \( (\epsilon_b \sim \text{several hundred keV}) \) if the energized particles have a Lorentz factor \( \sim 10^{5-6} \).

What is clear from the sample of bursts observed with BATSE’s Spectroscopy Detectors is that GRB spectra are typically well described by broken power laws with a turnover energy \( E_\circ \) ranging from below 100 keV to more than an MeV, but peaking under 200 keV with only a small fraction of the spectra breaking above 400 keV (Band et al. 1993). The impact of this spectral structure on the modeling of a cosmological population can
be substantial, particularly when comparing the catalogs from instruments with different energy windows, since the break feature necessarily redshifts into and out of the observed energy range at varying levels of sensitivity. We here consider this important effect and its implications on the cosmological hypothesis, and discuss the limits one may thereby reasonably place on the evolution of the comoving source density and luminosity function, and on the redshift range sampled by each detector. An earlier treatment of the impact of redshift on the observed spectra of individual bursts was presented by Paczyński (1992).

2. The Data Samples And Model Source Distributions

Due to the short time that BATSE has been collecting data, its catalog contains only a few of the important rare, strong bursts and must therefore be supplemented with bursts recorded by PVO, SMM, KONUS, SIGNE, and APEX. The use of data from multiple instruments (with uncertain relative sensitivities) introduces considerable complication due to varied burst identification criteria. In addition, intercomparison requires correction of the observed rates to full sky, live time equivalent rates. The \( \langle V/V_{\text{max}} \rangle \) test (Schmidt et al. 1988) allows comparison between disparate instruments despite uncertain relative sensitivities. \( V/V_{\text{max}} \) corresponds directly to a ratio of sampling volumes only in Euclidean space, and throughout the following discussion we will refer to this statistic as \( (F_{\text{min}}/F_{\text{max}})^{3/2} \) whether it is determined from peak photon or energy fluxes or fluences, except where the distinction is important. Each of the selected data sets (summarized in Table I) has a large sample of bursts, published \( \langle (F_{\text{min}}/F_{\text{max}})^{3/2} \rangle \) values and corrected detection rates \( R \). The errors in \( R \) were estimated by scaling the square root of the burst sample size from which \( R \) was determined and represent lower limits to the uncertainties.

The BATSE data currently available in the public domain are sufficiently detailed to allow the definition of two useful subsamples. In constructing each subsample, we have omitted bursts with incomplete information or with an overwrite flag.

The first, BATSE-15\( \sigma \), simulates a less sensitive detector by setting \( C_{\text{lim}} \) to 15 times the background uncertainty instead of the 5.5\( \sigma \) used for BATSE triggered sample (Meegan
et al. 1992) and still contains more than 100 bursts. The second subsample, BATSE-Ch4, consists of those bursts with a fluence in the fourth LAD spectral channel (300−≈1000 keV; Fishman et al. 1989), greater than 5.5 times the error in this fluence as listed in the burst catalog. Sub-sample detection rates were scaled from the BATSE rate based on the fraction of bursts which passed the secondary criterion.

Our analysis is based on models of the source distribution at cosmological distances similar to those discussed by, e.g., Mao & Paczyński (1992), but with the following important distinctions. First, while we only consider standard cosmologies with Λ = 0, we do permit q_0 to vary. Second and more significantly, we approximate the intrinsic burst spectrum as a broken (rather than a single) power law

\[ \nu L_\nu d\nu = \begin{cases} 
A\nu^{\alpha_1}d\nu & \nu \leq \nu_b \\
A\nu_b^{\alpha_1-\alpha_2}\nu^{\alpha_2}d\nu & \nu \geq \nu_b 
\end{cases}, \]

(1)

and integrate over a fixed detection bandpass \( \nu_1(1+z) \) to \( \nu_2(1+z) \). In their study of 54 bursts observed with BATSE, Band et al. (1993) found that the spectral index we label \( \alpha_1 \) ranges from 0.5 to 2.7 with the majority of the events at \( \approx 1 \), and that \( \alpha_2 \) ranges from more than 0 to less than \(-3\) with most of the bursts at just under 0 (see also Schaefer 1992). We assume the fiducial values of 1 and \(-1\) for these indices, respectively, for which Band et al.’s (1993) \( E_o \) (see §1 above) is then half the break energy \( E_b \) in the observer’s frame. The models we discuss assume an intrinsic break energy \( \epsilon_b \equiv h\nu_b = E_b(1+z) = 300 \text{ keV} \).

3. Analysis And Discussion

For each distribution, we use an iterative technique to identify BATSE’s limiting redshift \( z_{max} \), such that the corresponding value of \( F_{min} = F(z_{max}) \) gives the correct \( \langle (F_{min}/F_{max})^{3/2} \rangle \). This specifies the value of \( A \) relative to \( F_{min} \), and integration over the volume up to \( z_{max} \) fixes the density \( n_0 \) such that the rate \( \mathcal{R} \) matches that observed by BATSE. A model is generated by varying the limiting flux, simulating more or less sensitive detectors, and integrating \( \langle (F_{min}/F_{max})^{3/2} \rangle \) and burst rate out to the new limiting redshift. Predictions of what other experiments would measure are made by integrating over the same source distribution (with identical \( n_0 \) and \( A \)), but with \( F(z) \) integrated over
a different bandpass. Figure 1 shows the observed data points listed in Table I along with the corresponding $\langle (F_{\text{min}}/F_{\text{max}})^{3/2} \rangle - R$ curves for the simplest model with a spectral break (i.e., for a distribution of standard candle sources with a single intrinsic spectrum broken at $\epsilon_b = 300$ keV and uniformly distributed in a $q_0 = 1/2$ universe with no evolution). It is important to emphasize that without a spectral break, all the curves would be degenerate and could not meet all of the data points within the indicated $1\sigma$ error bars.

Though a single model source distribution is used for Figure 1, each data point is associated with a different curve because different instruments “see” different parts of the spectrum. To clarify the presentation, we can instead “K-correct” the data to a standard passband corresponding to the BATSE curve shown in Figure 2. To do this, we first construct a model as described above and estimate the limiting redshift for a given experiment so that enough sources are included to reproduce the observed rate. Then for each individual burst in each data set, its $(F_{\text{min}}/F_{\text{max}})^{3/2}$ and the corresponding instrument’s $F_{\text{min}}$ give the flux in the observed bandpass. The redshift of that source can be found in the case of a standard candle model with weak or no luminosity evolution because the flux is a monotonically decreasing function of $z$. The spectral model, redshifted appropriately, can be used to determine what flux $F_{\text{max},K}$ would be measured for that same burst in BATSE’s bandpass. The ratio of $F_{\text{max},K}$ over $F_{\text{min},K}$ then yields the K-corrected $(F_{\text{min}}/F_{\text{max}})^{3/2}_K$. Averaged over all the bursts in a sample, these give the corresponding K-corrected $\langle (F_{\text{min}}/F_{\text{max}})^{3/2}_K \rangle$ shown in Figure 2. For a single detector, the flux–distance relationship is systematically distorted (depending on the energy window) by the redshift of the break across the bandpass, i.e., more distant bursts have observed fluxes progressively lower than would be expected from the luminosity distance alone. Therefore, when the K-correction is invoked to directly compare $\langle (F_{\text{min}}/F_{\text{max}})^{3/2} \rangle$ vs. $R$ for different instruments, the calculated $\langle (F_{\text{min}}/F_{\text{max}})^{3/2}_K \rangle$ in this figure is different from $\langle (F_{\text{min}}/F_{\text{max}})^{3/2} \rangle$. SIGNE is not included on this plot because the data for individual bursts are not available.

If GRB locations correlate with luminous matter, their distribution might be expected to appear clumped on the sky. However, the angular correlation function for the burst
positions in two catalogs (Hartmann & Blumenthal 1989) does not show any clustering and indicates a minimum distance scale of $\gtrsim 100 \text{ Mpc}$ (or a minimum redshift $z_{\text{min}} \gtrsim 0.05$, see Eq. 1) for the fainter bursts. This suggests that the source population may be truncated with no members in the local universe. We therefore consider the implications of a truncated population by integrating from a non-zero minimum redshift $z_{\text{min}}$ when calculating the predicted $\langle (F_{\text{min}}/F_{\text{max}})^{3/2} \rangle - R$ curves, shown in Figure 3 including the K-corrected data points from Figure 2. This figure clearly illustrates that a population truncated at a $z_{\text{min}} \gtrsim 0.1$ is inconsistent with the available data and a simple cosmological source model. The brightest bursts must originate nearby if this model is valid.

4. Conclusions

In this paper, we have attempted to reconcile the various GRB catalogs with a single unifying cosmological source distribution and have shown that a simple model in which bursts have a spectral break at $300 \text{ keV}$ and occur in a population uniformly distributed in a $q_0=1/2$ universe with no evolution can account very well for all the observed characteristics. The qualitative aspects of our results are not changed by the inclusion of a model with a distribution in $\epsilon_b$, as long as this distribution peaks below $\sim 800 \text{ keV}$, but the fit improves as $\epsilon_b$ approaches $\sim 300 \text{ keV}$. Although the Ginga data set could not be included due to the absence of precise information concerning its dead time correction and field of view obscuration, we note that the estimated improvement of a factor of 2-3 in its sensitivity over KONUS and its observed value of $0.35 \pm 0.035$ in $\langle (F_{\text{min}}/F_{\text{max}})^{3/2} \rangle$ (Ogasaka et al. 1991) would place it between the BATSE-15$\sigma$ and BATSE data points in Figure 2, and would therefore be fully consistent with the model. We note that without consideration of the spectral break, the multiplicative probability that all of the data points are consistent with the simple cosmological curve is $\sim 0.01\%$. By comparison, the likelihood for consistency with a single model using the break improves to the significantly greater value of $\sim 3\%$. Even excluding the SMM value, these probabilities are 0.3% and 6%, respectively. These would presumably improve if the other differences between these ex-
periments (e.g. threshold effects and trigger time scales) and the intrinsic source properties (e.g. luminosity function) were incorporated into the analysis.

An equally important result of our analysis is the estimation of a maximum value for the minimum redshift \(z_{\text{min}}\) of the source population. We have seen that a distribution truncated at \(z_{\text{min}} \gtrsim 0.1\) is inconsistent with the combined body of data considered here. As such, the absence of M31-like galaxies within the error boxes of known burst locations (Schaefer 1992) might argue against a dominant association of GRB sources with large galaxies. However, these objects could reside in LMC-scale (or smaller) galaxies, which are known to be statistically associated with their larger brethren. The fields with the tight burster error boxes should be reanalyzed to determine if there is a statistical excess of large galaxies near the error boxes. This correlation would suggest that the sources are associated with small galaxies rather than with massive galaxy cores.

It is also possible to limit the evolution of GRB sources in the context of these models by requiring a 1\(\sigma\) fit to all the data sets previously described (Tamblyn & Melia 1993). Within the redshift of \(\approx 1\) sampled by BATSE, the differences introduced by reasonable \(q_0\) variations (i.e., \(0.1 \lesssim q_0 \lesssim 0.9\)) are dwarfed by evolutionary uncertainties. However, we remark on a potentially interesting future experiment that may be able to distinguish at least between the cases \(q_0 \sim 0.1\) and \(q_0 \sim 0.5\), provided only that there is no luminosity evolution in the source population, though other factors, such as number evolution, the break energy and \(z_{\text{min}}\) may vary. Assuming BATSE survives long enough to detect \(\approx 800\) bursts, so that \(n_0\) is known to roughly 10\%, a simple instrument with no directionality and roughly 18 times BATSE’s sensitivity in the same bandpass would detect a sufficient number of events in 3 years of full sky coverage to differentiate between the measured \(\langle(F_{\text{min}}/F_{\text{max}})^{3/2}\rangle\) for these two values of \(q_0\) at \(\geq 3\sigma\). Such an experiment might fall within the confines of a NASA SMEX mission as an appropriate follow-on to BATSE.

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| Experiment  | Bandpass (keV) | Sample Size | $R^\dagger$ (yr$^{-1}$) | $\langle (F_{min}/F_{max})^{3/2} \rangle$ | $z_{max}$ |
|------------|---------------|-------------|-----------------|-----------------|----------|
| PVO$^1$    | 100 – 2000    | 228         | 38± 3           | 0.46 ±0.02      | 0.2      |
| SMM$^2$    | 350 – 800     | 132         | 50± 5           | 0.40 ±0.025     | 0.3      |
| KONUS$^3$  | 50 – 150      | 123         | 130±12          | 0.45 ±0.03      | 0.4      |
| SIGNE$^4$  | 50 – 400      | 169         | 125±10          | 0.42 ±0.02      | 0.4      |
| APEX$^5$   | 120 – 700     | 58          | 115±16          | 0.39 ±0.04      | 0.4      |
| BATSE-Ch4$^6$ | 300 – ≈1000 | 43          | 168±26          | 0.35 ±0.044     | 0.4      |
| BATSE-15σ$^6$ | 50 – 300   | 115         | 430±43          | 0.384±0.029     | 0.7      |
| BATSE$^7$  | 50 – 300      | 153; 271    | 800±65          | 0.335±0.018     | 1.0      |

$^\dagger$Errors are based on Poisson statistics, with $\Delta R/R = \sqrt{N}/N$, where $N$ is the sample size

$^1$Chuang et al. (1992)
$^2$Matz et al. (1992); Matz (1993)
$^3$Higdon & Schmidt (1990); Matz et al. (1990)
$^4$Mitrofanov et al. (1991); Atteia et al. (1991)
$^5$Atteia et al. (1991); Mitrofanov et al. (1991); Mitrofanov et al. (1992)
$^6$Fishman et al. (1989); this work
$^7$Fishman et al. (1989); Meegan et al. (1992); Band (1993)
Figure Captions

**Fig. 1.** – Observed values of $\langle (F_{\text{min}}/F_{\text{max}})^{3/2} \rangle$ versus the detectable burst rate $\mathcal{R}$ for each of the 8 samples considered here. The relevant energy windows for the various detectors are indicated in the figure. The corresponding theoretical curves are calculated for the simplest model for BATSE normalization for $n_0$, consisting of a distribution of standard candle sources with a single intrinsic spectrum broken at $\epsilon_b = 300$ keV and uniformly distributed in a $q_0 = 1/2$ universe with no evolution. Each of the curves passes within 1 sigma of its associated data point.

**Fig. 2.** – Same as Figure 1, except that now only the curve corresponding to BATSE’s bandpass is shown. All the data points are K-corrected to this same energy window so that they too correspond to the single curve shown here. As was the case in Figure 1, all the data are within 1 sigma of the theoretical prediction.

**Fig. 3.** – Same as Figure 2, except that the theoretical curves are now calculated under the assumption that the source population is locally truncated, i.e., $\langle (F_{\text{min}}/F_{\text{max}})^{3/2} \rangle_K$ is determined by integrating from a non-zero minimum redshift $z_{\text{min}}$. A population truncated at a $z_{\text{min}} \gtrsim 0.1$ is inconsistent with the available data and a simple cosmology.
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