Are Gamma-Ray Bursts Cosmological?

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ABSTRACT

Gamma-ray burst sources are distributed with a high level of isotropy, which is compatible with either a cosmological origin or an extended galactic halo origin. The brightness distribution is another indicator used to characterize the spatial distribution in distance. In this paper we discuss detailed fits of the BATSE gamma-ray burst peak-flux distributions with Friedmann models taking into account possible density evolution and standard candle luminosity functions. A chi-square analysis is used to estimate the goodness of the fits and we derive the significance level of limits on the density evolution and luminosity function parameters. Cosmological models provide a good fit over a range of parameter space which is physically reasonable.

1. INTRODUCTION

The gamma-ray bursts are distributed isotropically on the sky (Fishman et al. 1994; Tegmark et al. 1996; Briggs et al. 1996; although a recent paper shows that at least one quadrupole term is non zero, Balázs, Mészáros and Horváth 1998), which is compatible with either a cosmological origin or an extended galactic halo origin; where the first origin seem to be more probable (Tegmark et al. 1996, Briggs et al. 1996). Recently, the successful identifications made by the Beppo-SAX satellite, followed by the detection of optical counterparts (van Paradijs et al. 1997), seem to give a firm support for the models aiming to explain the bursts by merging neutron stars (Usov and Chibisov 1975; Rees and Mészáros 1994; Mészáros and Rees 1997) and seem to put them definitely into the cosmological distances. In addition, the fainter bursts seem to have longer durations (Norris et al. 1995; Mészáros et al. 1996). Hence, all these seem to put the bursts definitely into the cosmological distances. Nevertheless, further proofs of cosmological origin are still useful. The search for a further support is the aim of this paper.

The brightness distribution is the indicator used to characterize the spatial distribution in distance, and this can also be used to test the cosmological hypothesis. This is generally done by investigation of the functional behavior of the integral number \( N \) of sources with peak photon flux rates \( P \) above a certain
value, $N(> P)$. Comparisons of observed versus expected values in Friedmann cosmologies have been discussed, e.g., by Mao and Paczynski (1992), Dermer (1992), Piran (1992) and Wasserman (1992). Statistical fits to a $\log N - \log P$ distribution have been done by Wickramasinghe, et al. (1993), Cohen and Piran (1994), Emssl and Horack (1994), Mészáros and Meszáros (1995), Loredo and Wasserman (1995), Horack, Emssl and Hartmann (1995), Fenimore and Bloom (1995), Horváth, Mészáros and Mészáros (1996), Mészáros and Mészáros (1996). One of the main questions that such fits must address is the size of the parameter space region which is compatible with a cosmological distribution, and whether such parameters are reasonable. If the acceptable region contains physically plausible parameters and is not too restricted, one may assume the consistency of the observations with a general type of models; if, on the other hand, the acceptable region is very small and/or populated mainly by physically implausible parameters, fine-tuning would be required to fit the observations, and the case for consistency with those models is weaker. Such consistency, and absence of fine-tuning, is a requirement expected of any successful model of the GRB distribution, whether cosmological or galactic. Here, we shall address only the question of the consistency of the number distribution under the hypothesis of a cosmological distribution with a standard candle luminosity distribution.

Most cosmological fits have been made with relatively specialized models, generally either with non-evolving or evolving density standard candle models, or with non-evolving luminosity functions. Limits on the luminosity function were investigated in cosmology with a pure density evolution by Horack, Emssl and Hartmann (1995) using a method of moments. In Euclidean space, limits have been investigated by Horack, Emssl and Meegan (1994), Ulmers and Wijers (1995) and Ulmer, Wijers and Fenimore (1995). Most cosmological calculations have used either the 1B or the 2B BATSE data base. In the present paper we make detailed chi-squared fits of the observed brightness distribution. This is done both using the BATSE 2B catalogue of sources (Meegan et al. 1996), and combining the BATSE catalogue with information published for the PVO counts (Fenimore and Bloom 1995). The significance levels of the various cosmological fits is discussed for both the 2B and the expanded burst sample.

Note that, as it seems, there are several subclasses of gamma-ray bursts (Kouveliotou et al. 1993; Dezalay et al. 1996; Pendleton et al. 1997; Mészáros et al. 1998; Bagoly et al. 1998). Nevertheless, the criteria are still ambiguous. Therefore, in this article these subclasses will not be considered.

## 2. MODELS AND FITS

Analytical expressions for the integral burst number counts $N(> P)$ with peak photon flux rate in excess of $P$ (units of photon $cm^{-2}s^{-1}$) were discussed by Mészáros and Mészáros (1995) and by Mészáros and Mészáros (1996) for arbitrary Friedmann models with zero cosmological constant. As discussed in
Mészáros and Mészáros (1995), effects of a non-flat cosmology ($\Omega_o < 1$) are small, and to a first approximation can be neglected. Below we assume $\Omega_o = 1$ everywhere. The effect of a pure density evolution is approximated through a dependence

$$n(z) = n_o(1 + z)^D,$$

where $n$ is the physical burst density rate in cm$^{-3}$yr$^{-1}$, $n_o$ is the density rate at $z = 0$ ($D = 3$ corresponds therefore to a non-evolving, constant comoving density). It is assumed that the sources have the same intrinsic luminosity $L_o$. Therefore the photon luminosity function in the 50-300 keV range is represented by the form,

$$\Phi(L) = n_o \delta(L - L_o)$$

(2)

For the rest of the paper we take $P$ to be peak photon flux [cm$^{-2}$s$^{-1}$], $n_o$ is the physical density of bursts per year at $z = 0$.

The integral number distribution of bursts per year with peak flux rate above $P$ is given by Mészáros and Mészáros (1995) as

$$N(> P) = \frac{4\pi L_o^{3/2} n_o}{3 (4\pi P)^{3/2}} I,$$

(3)

where $I$ is a dimensionless analytical function of $P$ and the model parameters, i.e. the luminosity function parameters $L_o$, the density evolution parameter $D$, and the density $n(0) = n_o$.

For the numerical fits we used the BATSE 2B catalog (Meegan et al. 1996). The 1024 ms peak fluxes $P$ (photons cm$^{-2}$s$^{-1}$) were used, and only events with peak count rates divided by threshold count rates $C_{max}/C_{min} > 1$ were included, where $C_{min}$ is the published count threshold for each event (Meegan et al. 1996). The 2B sample with this criterion consists of 278 entries in the catalog. Applying the efficiency tables published with the catalog to correct for detector inefficiency near the trigger threshold, the nominal number of bursts accumulated by BATSE over a period of two years with peak fluxes above log $P \geq -0.6$ is 369. We chose for these bursts a binning equidistant in log $10 P$, with step size 0.2 between -0.6 and 1.2, which gives 9 equal bins with a minimum number of 7 events per bin (in the highest $P$ bin, log$_{10} P = 1.0$ to 1.2) for the two year 2B sample. The fits were made to the differential burst number distribution $N(P)$ as a function of peak photon flux $P$ (since only in the differential distribution may the bins be considered independent of each other for a $\chi^2$ fit) and the errors in each bin were taken to be the square root of the number of events in that bin.

Some of the fits were made using an extended 2B plus PVO sample. For the PVO events, we used the PVO portion of Table 2 of Fenimore and Bloom (1995) for log$_{10} P \geq 1.2$. A number of subtle issues concerning a matching between the different PVO and BATSE data sets are discussed by Fenimore et al. (1993), who indicate that systematic uncertainties of $\pm 10\%$ in the relative
normalization cannot be ruled out. The matching of the level of the BATSE and PVO curves was taken directly from Fenimore and Bloom (1995). The PVO data was rebinned, ignoring PVO bursts below $\log_{10} P = 1.2$ so as not to count twice, and its level was renormalized so that the matching 2B data had the same level as in the original 2B catalog, i.e. about 2 years. The errors for the PVO sample were also renormalized taking into account the fact that data had accumulated over more than ten years in the PVO case, keeping the relative errors the same. We used 5 bins in the PVO range, so that the combined 2B+PVO fits have 9+5=14 bins, reaching up to $\log_{10} P = 3.0$.

The fits (standard candle with density evolution) involve the fewest parameters: the photon luminosity $L_o$ (ph/s), the density $n_o$ and the density evolution parameter $D$. For the 2B sample between peak fluxes $-0.6 \leq \log P \leq 1.2$, the free parameters are $p = 3$ the degrees of freedom are $f = 6$ and the best $\chi^2_{\text{red}}$ (reduced chi-square or $\chi^2$ divided by degrees of freedom) is 0.85 at the innermost mark. The 1σ, 2σ, 3σ significance contours were determined using the standard prescription (e.g., Press, et al., 1986, or Lampton, Margon and Bowyer 1976). The fit (Fig. a) is good over an elongated region describing a relation between the luminosity and the density evolution. For faster density evolution $n \propto (1 + z)^D$ (larger $D$) the luminosity must increase because most sources are at larger redshifts, while for slower or negative evolution the luminosity must decrease, since most sources are at small redshift ($D = 3$ is constant comoving density). The optimal fit is obtained for $D = 3.5$ and $L_o \sim 10^{57} \text{s}^{-1}$. This luminosity is close to the standard candle value deduced, e.g. Horack, Emslie and Hartmann (1995) and Fenimore and Bloom (1995). (corresponding to $L_o \sim 10^{53} \text{ergs}^{-1}$ for typical photon energies of 0.5 MeV). However the preference for $D = 3.5$ was not, as far as we can tell, encountered in previous fits. The $\chi^2_{\text{red}}$ around the best fit minimum is 0.85; however, the 1σ region around it is rather large, even if not very wide, so this preference is not strong.

The fits using the 2B+PVO sample ($p = 3$, $f = 11$) are shown in Fig. b, with a best $\chi^2_{\text{red}} = 0.62$ at the central mark enclosed by its 1σ, 2σ, 3σ contours. We note that this ignores any possible systematic errors in matching BATSE and PVO beyond what is done in Fenimore et al. (1993), and Fenimore and Bloom (1995). If any extra errors were present, they could in principle increase the size of the significance regions discussed below (e.g. it might add an extra free parameter for the relative normalization). However, such errors are extremely difficult to quantify without going into additional details of the instruments, and we follow Fenimore and Bloom (1995) in adopting their relative normalization as adequate without further manipulation. The effect of the rare high flux PVO bursts satisfying a tight $N \propto P^{-3/2}$ correlation at $1.2 \leq \log_{10} P \leq 3.0$ is to improve the best fit (lower $\chi^2_{\text{red}}$) and to place it at a somewhat smaller luminosity $L_o \sim 5 \times 10^{56} \text{s}^{-1}$ and closer to comoving constant density evolution, $D \sim 3$. This is in good agreement with Fenimore and Bloom’s (1995) value of $L_o \sim 5 \times 10^{56} \text{ergs}^{-1}$. However, as seen from Fig. b, the 1σ region around this best fit minimum is compatible with both larger and smaller $L_o$ and $D$. In
contrast to the pure 2B fit, however, the joint 1σ upper limit for $L_0$ and $D$ are $L_0 \leq 5 \times 10^{57} \text{s}^{-1}$, $D \leq 4.5$ (or 3σ joint upper limits $L_0 \leq 5 \times 10^{58} \text{s}^{-1}$, $D \leq 5$).

3. CONCLUSION

The fits presented above show that a cosmological interpretation is compatible with the data under a variety of assumptions. Good fits of the observed differential distribution of bursts $N(P)$ as a function of peak photon flux $P$ are obtained under a standard candle luminosity function assumption. Fits were obtained for a range of density evolution indices $D$, defined through a physical density dependence $n_o \propto (1 + z)^D$ where $D = 3$ is equivalent to a non-evolving, constant comoving density case. The cosmological fits obtained are of good quality ($\chi^2_{\text{red}} \sim 1$) for a range of plausible model assumptions.

The present results are in significant agreement with the literature (Horack, Emslie and Meegan 1994, Horack, Emslie and Hartmann 1995, Ulmer, Wijers and Fenimore 1995, Hakkila et al. 1995, Horváth, Mészáros and Mészáros 1996).

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Figure Caption

Cosmological fits for \( \Omega = 1, \Lambda = 0 \) for standard candle photon luminosity \( L_0 \) (photon/s) and physical density evolution \( n(z) \propto (1+z)^D \). The inner dots are the best fit \( \chi^2_{\text{red}} \) minimum location, with \( 1\sigma, 2\sigma, 3\sigma \) contours increasing outwards. a) Top: using the BATSE 2B data base; b) Bottom: using the 2B plus PVO information.