LA-UR-00-12

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Title: The Energy Distribution of GRBs

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Submitted to: Proceedings of the 5th Huntsville Gamma Ray Burst Symposium
(October 18-22, 1999)

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The Energy Distribution of GRBs

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Abstract. We analyze the distribution of total energy of bursts with optical afterglows. Our sample contains eleven bursts for which there are BATSE data allowing detailed fits to the spectra. Six of these bursts have measured redshifts while five have host galaxies whose redshifts are unknown. Using a new technique based on the distribution of magnitudes of observed high redshift galaxies, we bracket the expected redshifts of these host galaxies. We perform a maximum likelihood fit for the energy distribution of these GRBs. Assuming that the total energy emitted has a log-normal distribution, we find that the average isotropic energy emitted is $E_\gamma = 1.5^{+1.5}_{-0.6} \times 10^{53}$ ergs (for $H_0 = 65$ km s⁻¹ Mpc⁻¹, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$) with a standard deviation $\sigma_\gamma = 1.2^{+0.6}_{-0.4}$. The corresponding distribution of X-ray afterglow energy (for seven bursts) is significantly narrower with $\sigma_x = 0.5^{+0.4}_{-0.25}$ and $E_x = 3.8^{+2}_{-1.5} \times 10^{51}$ ergs, in agreement with the prediction of the patchy shell model of Kumar and Piran [1]. We also give a table with the detailed fits to the spectra of the 11 GRBs with optical afterglow with BATSE data.

The energy and luminosity functions of GRBs are among the most interesting still unknown parameters of these objects. Clearly a good estimate of the total energy emitted in these bursts could shed a lot of light on possible sources. Until recently the absence of a measured burst distance hindered the calculation of the total energy radiated by a burst. However we have now determined the redshifts of some of the host galaxies associated with a number of bursts. We have expanded this sample by estimating the redshifts of host galaxies without measured redshifts based on their apparent magnitudes. With this sample of bursts with estimated energy emission we can calculate the distribution of energy emitted. One has to remember though that this estimate is valid only for the subclass of GRBs with observed optical afterglows.

I GRB DATA

We consider the sample of GRBs with an observed optical afterglow and with a detected host galaxy with or without a measured redshift. To obtain a uniform

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TABLE 1. Main properties of the sample of Gamma Ray Bursts.

Name	N_0	α	β	E_0	F_γ^a	slope _x	F_x	t	R_{gal}	z_{obs}	z_{est}
	10^{-2}			keV	$10^{-6} \frac{\text{ergs}}{\text{cm}^2}$		$10^{-6} \frac{\text{ergs}}{\text{cm}^2}$	sec			
970228	...	...	...	...	...	...	...	...	24.6	0.695	0.8
970508	0.173	-1.191	-1.831	480.84	3.17	-1.2	0.39	23.44	25.8	0.835	1.2
970828	1.15	-0.704	-2.072	229.74	96	-1.0	1.82	146.59	24.5	0.958	0.8
971214	0.723	-0.783	-2.574	155.96	9.44	-1.6	1.31	45.45	25.5	3.412	1.2
971227	1.06	-1.440	-4.198	112.03	1.21	...	...	6.94	25.0	...	1.2
980326	2.11	-1.327	-4.335	77.19	0.92	...	...	4.01	25.3	...	1.2
980329	2.58	-0.964	-2.431	235.65	55.1	-1.34	0.56	50.15	26.3	...	1.2
980425	0.47	-1.266	...	161.20	4.96	...	...	37.41	14.3	0.0085	0.01
980519	0.479	-1.352	...	315.94	10.3	...	...	56.35	24.7	...	0.8
980613	...	...	...	...	...	-1.6	0.55	...	24.4	1.096	0.8
980703	0.441	-1.314	-2.396	370.26	22.6	-1.67	1.27	102.37	23.0	0.967	0.6
990123	2.62	-0.900	-2.476	549.51	268	-1.6	8.98	104.61	24.3	1.600	0.8
990506	1.51	-1.370	-2.152	449.78	194	...	...	220.38	...	1.2	...
950510	0.796	-1.275	-2.670	174.24	22.6	...	...	103.84	...	1.619	...
990712	...	...	...	...	...	...	...	...	22.0	0.43	0.40

^a 20-2000keV

estimate of the energy fluence we consider only those bursts detected by BATSE. For these bursts we obtain a best fit to the spectrum of the entire burst, which is described by the Band function [2]. The parameters of the bursts, including the parameters of the Band function are given in Table 1.

Only six out of the eleven BATSE bursts with an optical afterglow and a host galaxy have a measured redshift (mostly measured for the associated host). In order to increase the number of relevant bursts and to improve the statistics, we implement here a method to determine the redshift of those host galaxies for which there are currently no spectroscopic redshifts.

In addition to the energy emitted by the burst (mostly in γ -rays), significant emission occurs during the first few hours of the afterglow (mostly in X-rays). We estimate this energy (excluding the prompt X-ray emission) using the observed late (few hours) X-ray flux and assuming this emission decays as a power law with the index “slope_x” shown in the above table over the period 100 to 10^5 seconds after the burst.

II REDSHIFT DETERMINATION.

The use of photometry to derive galaxy redshifts has flourished during the past 5 years (e.g. [3–6]). It is now common to determine redshifts to an accuracy of 10% (e.g. [7]) by using multi-band photometry (usually 4 to 6 bands). It is therefore fair to say that multi-band photometry is an economical way of determining redshifts. Unfortunately, in the case of GRB hosts one is limited, in most cases, to

FIGURE 1. The redshift distribution of galaxies in the R band from the HDF (see text). The average redshift (z_{avg}) has been obtained from the maximum of the polynomial fit (solid curves) to the observed data and the errors reflect the redshift for which the solid curve encloses 68% of the area.

observations in one band (typically R).

In principle it may seem futile to try to determine the redshift of a galaxy from a single band. Galaxies span a large range in stellar masses (i.e. luminosities) and therefore it is possible to find galaxies of a given magnitude at virtually any redshift (c.f. [8]). On the other hand, since the volume element dV/dz peaks at around $z = 1 - 2$ (for reasonable cosmologies) and galaxies formed stars at a higher rate at $z > 1$ (and therefore were brighter), one expects galaxies are more likely to inhabit the $1 < z < 2$ region for not too faint (or too bright) magnitudes. In this paper we use the Hubble Deep Field (HDF) observations to calibrate an approximate redshift-magnitude relationship. In doing so we assume that GRB hosts belong to the general galaxy population.

In Fig. 1 we show the redshift distribution of the HDF [8] galaxies as a function of apparent magnitude R . We have transformed the HST F606W magnitudes into cousins R magnitudes. First inspection shows that for $R < 26$ galaxies are systematically more common at $z < 2$ than at higher redshifts, as expected. Note that the average redshift increases with galaxy magnitude.

A concern is that the HDF is *not* a volume limited sample, as illustrated by Fig. 1 in [8]. Clearly the HDF is missing only very bright galaxies at $z < 0.5$, which will not affect our redshift estimates as GRB hosts are much fainter in general (see

FIGURE 2. The 1σ confidence region in the 20–2000 keV band (left panel). Right panel: same as left panel but for the X-ray energy. In this case we have integrated the X-ray light curve between 100 and 10^5 seconds.

Table 1). Note that while Fig. 1 in [8] might lead you to suspect that a large number of $z > 1$ galaxies may be missing, luminosity evolution shows this is not the case. At $z > 1$ galaxies were forming many more stars than at $z < 1$ (e.g. [9,10]), and thus they were more luminous (by 2-3 magnitudes [10]) than nearby galaxies. Thus we conclude that for $R < 26 - 27$ the HDF represents a fair sample of the Universe. A statistical redshift-magnitude relationship is justified by the relative paucity of $z < 0.5$ galaxies in the redshift distributions for faint magnitudes $24 < R < 27$.

To evaluate the error of our redshift estimate, we compare the estimated redshifts z_{est} with the spectroscopic redshifts z_{obs} for those bursts where both are available (see Table 1). The differences between these two redshifts are comparable to the widths of the redshift distributions in Fig. 1. The major exception is GRB971214, where the estimated redshift is much lower than the spectroscopic one. Therefore we conclude that we can estimate redshifts (*statistically*) from one band within a 40% error.

III RESULTS AND CONCLUSIONS

We assume that the probability for a GRB to have an energy E_i in the interval E_i to $E_i + dE_i$ is given by a log-normal distribution with two parameters E_{av} and $\sigma(\log E)$. We use a maximum likelihood method to determine these two parameters. For half of our samples the redshift is only known within a 40%. To reflect this uncertainty we modify the log-normal probability distribution to allow for errors in the redshift (energy) determination by simply assuming that these errors are normally distributed. Then the likelihood function that we maximize is:

$$\ln \mathcal{E}(E_{av}, \sigma) = \sum_i \ln \left[\frac{1}{2\pi\sigma_i\sigma} \int \frac{\exp \left[-\frac{1}{2} \left[\frac{(\ln(E) - \ln(E_{av}))^2}{\sigma^2} + \frac{(E_i - E)^2}{\sigma_i^2} \right] \right]}{E} dE \right] \quad (1)$$

where σ_i is the error due to the redshift uncertainty of the burst i ; for the bursts with spectroscopic redshifts $\sigma_i=0$ and the integral over E becomes the evaluation of a δ function.

For the gamma-ray band we estimate the characteristic isotropic energy, E_γ , and its spread, σ_γ , in the 20–2000 keV band (Fig. 2, left panel). The preferred value for E_γ is 1.5×10^{53} erg with $\sigma = 1.2$. Recall that this is the standard deviation of a log-normal distribution, thus this value corresponds to a spread of about two and a half decades in energy. Note that there is no need to K-correct the data in this case because the 20–2000 keV band already contains most of the energy of the GRB.

We also perform a similar analysis for the X-ray energy between 100 and 10^5 seconds after the burst. The right panel of Fig. 2 shows the 1σ confidence contour. Note that the *variance* ($\sigma \sim 0.5$) is *significantly smaller than that for the gamma ray band*. This is in agreement with the theoretical predictions of the patchy shell model [1].

We have determined the luminosity function of GRBs with observed optical afterglow. In agreement with the predictions of the patchy shell model [1] the γ -ray energy emitted during the GRB has a significantly wider distribution than the X-ray energy emitted during the afterglow. It is interesting to compare our results with the luminosity function determined for the whole GRB sample. Schmidt [11] finds for a broken power law distribution that the characteristic energy (the position of the break) is 1.2×10^{53} ergs. This is very close to our average energy. The average energy in Schmidt's distribution is about factor of five smaller than its characteristic energy. These results are compatible since the subsample of bursts with observed afterglow, which we examine, is much brighter than the whole sample.

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