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Multi-band Observations of Gamma Ray Bursts

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Abstract. This talk focuses on the various aspects we learnt from multi-band observations of GRBs both, before and during the afterglow era. A statistical analysis to estimate the probable redshifts of host galaxies using the luminosity function of GRBs compatible with both the afterglow redshift data as well as the overall population of GRBs is discussed. We then address the question whether the observed fields of GRBs with precise localizations from third Inter-Planetary Network (IPN^3) contain suitable candidates for their host galaxies.

Key words. Gamma rays: bursts—CCD: observations—Methods: statistical.

1. Studies before the afterglow era

In 1994–95 we undertook a program to carry out an optical survey of a few GRB fields chosen from the IPN^3 catalog (Hurley 1995, private communication; Laros *et al.* 1998; Hurley *et al.* 2000). Deep CCD imaging of these fields was carried out at the 2.34 m and 1.02 m telescopes of Vainu Bappu Observatory (VBO), Kavalur until 1998. It was an attempt to identify the transient/quiescent counterparts of GRBs on the basis of photometric studies. For details on observations and photometric data analysis see Bhargavi (2001). In similar investigations the observers either looked for peculiar objects (Vrba *et al.* 1995) or an over-abundance of certain class of objects (Larson 1997) in their deep imaging surveys of IPN GRBs. None of our efforts led to an identification of a GRB counterpart.

Indeed, observational investigations were biased by the theoretical predictions (also vice versa), as it can be seen in the literature the earliest searches focussed on looking for Galactic objects where as those performed in 90s (after BATSE announced the first results) began to look for extra-galactic objects as possible sources of GRBs. In reality, the search strategies were rather vague due to our lack of knowledge of the nature of GRBs or their accompanying optical emission. Therefore it was not straight forward to associate an object to a GRB phenomenon.

Subsequent to the launch of the *BeppoSAX* satellite, which provided accurate sky co-ordinates within a few hours after the burst, the afterglow studies of GRBs have shown that fading Optical Transient (OT) is observable over a couple of months from ground-based optical telescopes (although with HST and in radio band the observations may be extended up to $\sim$year) and therefore one can safely rule out the possiblity of detecting any possible transient counterpart associated with IPN^3 GRBs in the CCD frames observed several years after the burst. Afterglow studies have also shown that

GRBs are hosted by faint galaxies at cosmological distances. In any given field of $\sim 10' \times 10'$ area one may find several faint galaxies and the number would increase as one observes deeper and deeper. However, it is difficult to pin down any of these objects as definite host of a GRB that occurred a few years ago. This is because the host galaxies neither show any evidence of burst in their quiescent state (i.e., OT does not leave behind any signature identifiable by optical observations after several years), nor exhibit any 'unusal' properties.

2. Luminosity function of GRBs

In an attempt to identify the potential candidates for the host galaxies of GRBs in our observed fields, we first ask what is the most probable redshift of the host galaxy of a GRB, given the γ-ray flux? This requires knowledge of the luminosity function of GRBs. Until recently one could detemine the luminosity function of GRBs from the number-count v/s flux ($\mathcal{N} - F$) relation. The optical afterglow observations have allowed redshift measurements for $\sim$ 17 GRBs. In an analysis to detemine the luminosity function of GRBs Sethi & Bhargavi (2001) identified a luminosity function that is compatible with both the samples: **(a)** redshift distribution of GRBs with observed afterglows **(b)** number-count v/s flux ($\mathcal{N} - F$) relation of overall population of GRBs. While they considered Schechter, scale-free and log-normal luminosity distributions each with several evolutionary as well as no-evolution models using $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 65\,\mathrm{km\,sec^{-1}\,Mpc^{-1}}$ cosmology, they found that only log-normal distribution is compatible with both (a) and (b) samples.

In the present analysis a few changes from the previous work of Sethi & Bhargavi (2001) have been incorporated: first, an additional factor of $(1+z)^{-1}$ has been introduced in their equation (3) which comes from cosmological time dilation of the rate of GRBs. Secondly, $p(z)$ in their equation (8), probability that burst of a given flux will occur in a redshift range of z to $z+dz$ here, is a joint redshift-flux probability $P(z, F)$.

Assuming a simple number density evolution the number of GRBs in the redshift range z and $z + dz$ and in the luminosity range L and $L + dL$ can be factorized as

$$N(z, L; a_i)dLdz = n(z)4\pi r^2 \frac{dr}{dz}\Phi(L; a_i)dLdz \tag{1}$$

a_i stands for the parameters of the luminosity function (e.g., σ and L_0 for the Log normal distribution). Here $n(z) = n_0(1+z)^\gamma$ is the comoving number density of GRBs up to a maximum redshift $Z_{\max}$ and $\Phi(L)$ is the non-evolving luminosity distribution. Using $L = 4\pi D_L^2 F$, we can get the number of GRBs in the redshifts range and the flux range F and $F + dF$:

$$N(z, F; a_i)dFdz = n_0(1+z)^\gamma 4\pi r^2 \frac{dr}{dz}\Phi(L; a_i)\frac{dL}{dF}dFdz. \tag{2}$$

Note that the Jacobian of transformation from $\{z, L\}$ to $\{z, F\}$ is simply $(dL/dF)_z$. For converting this into joint probability $P(z, F)$ of observing a source with flux in the range F and $F + dF$ and redshift range z and $z + dz$ one must divide $N(z, F)$ by the normalizing factor:

$$\mathcal{N} = \int_0^{z_{\max}} dz \int_{F_{\min}}^{\infty} dF N(z, F; a_i). \tag{3}$$

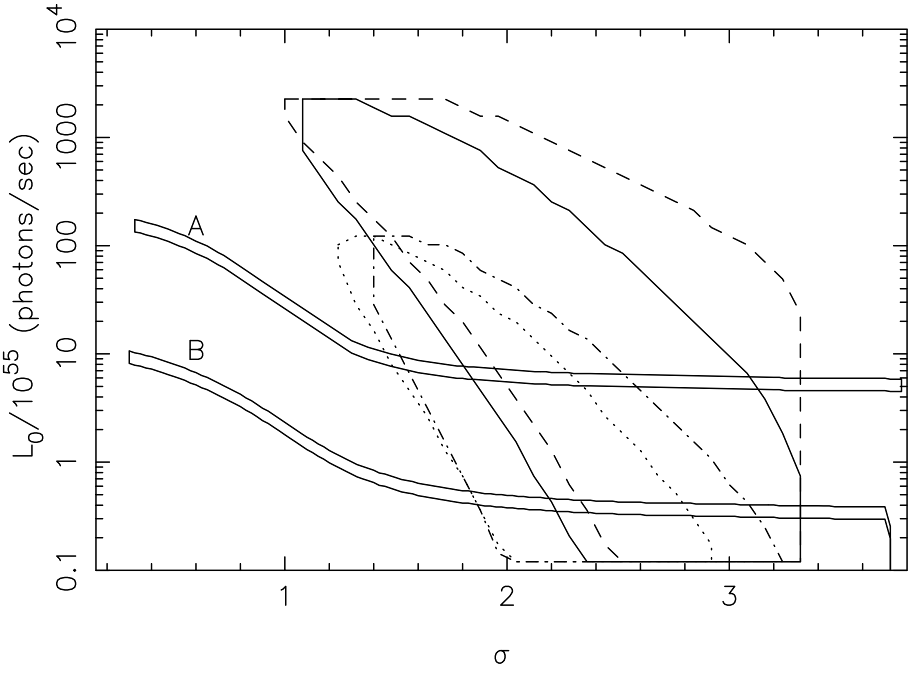

Figure 1. The results for the log-normal luminosity function are shown. The narrow regions (A, B) come from the N–F analysis and represent the region of K-S probability $P_{ks} > 0.01$ for the consistency between observed and theoretical number count-flux relation. We show the curves for no-evolution (B) and strong evolution (A) models. The broader regions (corresponding to $\approx$ 99% confidence level) come from afterglow analysis. They correspond to: no evolution model with no beaming correction (solid line), no evolution model with beaming correction (dotted line), strong evolution model with no beaming correction (dashed line) and strong evolution model with beaming correction (dot-dashed line).

For our analysis we take $z_{\rm max} = 5$ and $F_{\rm min} = 0.05$. The results are not very sensitive to the values of $z_{\rm max}$, $F_{\rm min}$. The joint probability is:

$$P(z, F; a_i)dFdz = \frac{N(z, F)}{\mathcal{N}} dzdF. \tag{4}$$

The likelihood that the observed set of 16 GRBs arise out of any assumed luminosity function is given by:

$$\mathcal{L}(a_i) = \prod_{j=1}^{16} P(z, F; a_i). \tag{5}$$

We need to maximize $\mathcal{L}(a_i)$ with respect to the parameters, $\{a_i\}$. Fig. 1 shows the results of such an exercise for log-normal distribution indicating regions where $\mathcal{L}(a_i)$ exceeds 10^{-4} times the value at the maximum (i.e., $\approx$ 99% confidence level). Also note that the allowed regions become narrower after beaming correction has been applied.

Table 1. Probable redshift range: IPN GRBs .

GRB	Peak flux $ph/cm^2/s$	$\langle z \rangle$ for $L_0(\mathrm{sec}^{-1})$ 10^{55}	10^{56}	Limiting magnitude	Z-range (mean $\pm 1\sigma$)
GRB 920720	15.437	0.16	0.42	B = 22.8	0.26 – 0.62
GRB 920517	38.757	0.11	0.29	B = 22.0	0.19 – 0.53
GRB 920525	22.64	0.14	0.36	V = 22.7	0.28 – 0.64
GRB 920325	13.75*	0.17	0.44	R = 20.9	0.18 – 0.5

*Flux was converted from the observed 25–100 keV range to the BATSE range (50–300 keV) using the method discussed in Bhargavi (2001).

2.1 *Estimation of redshifts*

Using the best-fit parameters $10^{55}\,\mathrm{sec}^{-1} \leq L_0 \leq 10^{56}\,\mathrm{sec}^{-1}$ and $2 \leq \sigma \leq 3$ for log-normal distribution, where L_0 is the average photon luminosity and σ is the width of the luminosity function, we calculate the average redshift and the variance of the expected redshift of the GRB of a given flux as follows:

$$\langle z \rangle = \int_0^\infty z p(z)\, dz\,; \quad \sigma = \int_0^\infty (z - \langle z \rangle)^2 p(z) dz \tag{6}$$

In Table 1 we show fluxes of 4 IPN GRBs and the range of their redshifts (columns 3 & 4). The redshifts lie in the range 0.1–0.4 when L_0 is varied between 1 and 10 in units of $10^{55}\,\mathrm{sec}^{-1}$. The variances are close to the mean value.

Similarly, we estimate the average redshift and variance for a sample of galaxies in a magnitude-limited sample. The relation between apparent magnitude m and absolute magnitude M is:

$$M = m - 25 \log_{10}(r/1\,\mathrm{Mpc}) - 2.5 \log_{10}(1+z) - m_K(z, \lambda) \tag{7}$$

m_K is the K-correction for galaxies and is a function of the redshift and the wavelength λ of the observed band. We apply these from Coleman, Wu & Weedman (1980). Given the absolute magnitude, the luminosity ($\mathrm{erg\,sec}^{-1}$) in different wave bands can be calculated using:

$$L_\lambda = L_\odot \times 10^{[0.4 \times (C - M_\lambda)]}. \tag{8}$$

Here $L_\odot = 4 \times 10^{33}$ is the bolometric luminosity of the Sun. The value of C has been taken to be 5.41, 4.79 and 4.49 respectively for B, V and R band filters.

The luminosity function of galaxies in B-band and its evolution for $z \leq 1$ is taken from Loveday *et al.* (1992) and Lilly *et al.* (1995). The luminosity function in other wave-bands can be obtained by using the spectral energy distribution given by Yoshii & Takahara (1988). For simplicity we assume the galaxy spectral distribution to remain unchanged for $z \leq 1$.

The redshift range for a given magnitude limit for the four IPN fields is given in column 6 of Table 1. The range refers to the 1σ deviation from the mean redshift. Comparing this with the redshift range in columns 3 & 4 of Table 1 we notice that the redshift range corresponding to the limiting magnitude of observed field overlaps with the redshift range from which the GRBs originate in all four cases. Therefore the GRB host might lie in the observed field.

If GRBs are associated with galaxies then it is natural to ask whether the observed fields have any plausible candidates for the GRB hosts. Most of the previous studies assumed GRBs to be standard candles, while our study shows that the GRB luminosity function is quite broad. This basically means that the redshift range from which the GRBs originate is also quite broad, as is evidenced by Table 1. Therefore some of the objects seen inside the error boxes could be the host, but we cannot rule out the possibility of the host being fainter than the magnitude limit of the survey. Moreover, since the z ranges compatible with the survey limits are marginal to the actual distribution of measured z, it is not likely that the host is detected in all the 4 error boxes.

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