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Luminosity evolution in gamma-ray bursts(*)

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Summary. — We estimate the luminosity evolution and formation rate for over a 900 BATSE GRBs by using redshift and luminosity data calculated by Band, Norris, and Bonnell (*ApJ*, **613** (2004) 484B) via the lag-luminosity correlation. By applying maximum likelihood techniques, we are able to infer the true distribution of the parent GRB population's luminosity function and density distributions in a way that accounts for detector selection effects. We find that after accounting for data truncation, there still exists a significant correlation between the average luminosity and redshift, indicating that distant GRBs are on average more luminous than nearby counterparts. This is consistent with previous studies showing strong source evolution and also recent observations of under luminous nearby GRBs. We find no evidence for beaming angle evolution in the current sample of GRBs with known redshift, suggesting that this increase in luminosity cannot be due to an evolution of the collimation of gamma-ray emission. The resulting luminosity function is well fit with a single power law of index $L'^{-1.5}$, which is intermediate between the values predicted by the $k = 2$ power law and Gaussian structured jet models. We also find that the GRB comoving rate density rises steeply with a broad peak between $1 < z < 2$ followed by a steady decline above $z > 3$. This rate density qualitatively matches the current estimates of the star formation rate at high redshifts, favoring a short lived massive star progenitor model, or a binary model with a short delay between the formation of the compact object and the eventual merger.

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1. – Introduction

There are currently roughly 30 gamma-ray burst events (GRBs) for which we have independently measured redshifts. From this small sample, it is already abundantly clear that the isotropic equivalent energy E_{iso} and luminosity L_{iso} are not standard candles.

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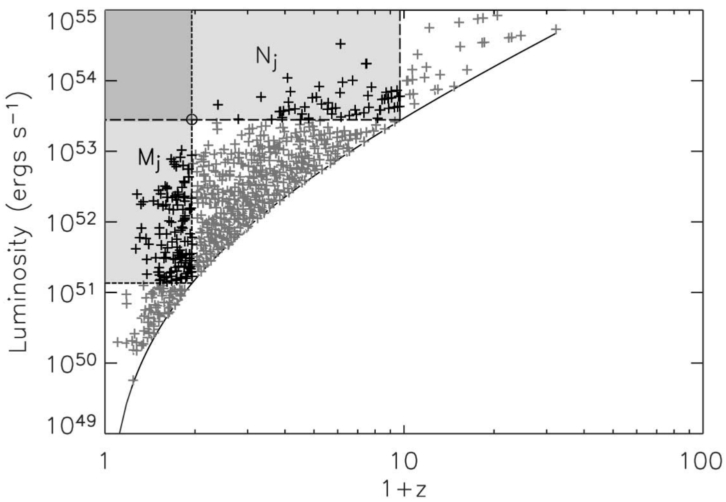

Fig. 1. – The associated sets used in the Lynden-Bell technique. For each data point with (L_i, z_i), the solid line represents the minimum luminosity or maximum redshift that the burst could have had and still have been observed.

Recently Sazonov, Lutovinov, and Sunyaev (2004) [1] and Soderberg *et al.*(2004) [2] have reported on observations of a nearby under luminous GRB occurring at redshift of $z = 0.106$ leading to speculation that there is either a substantial undetected dim population of GRBs or that the evolution of the average energy emitted by a GRB has evolved with time. A measure of the luminosity evolution in the GRB population may yield important clues regarding how GRB progenitors have evolved with time. Any attempt at quantifying the evolution of intrinsic source properties of parent populations must account for Malquist type biases. Detection thresholds prevent events below a certain flux from being observed resulting in the detection of only bright objects at large distances. Fortunately, straightforward methods have been devised to account for such effects based on maximum-likelihood techniques. These methods allow for the correct estimation of the correlation strength between a truncated data set as well as an estimate on the underlying GRB luminosity function and comoving rate density, both of which can give us information about the nature of GRBs and their progenitors

2. – Analysis

We examine the issue of luminosity and density evolution by using a sample of over 900 BATSE GRBs for which the luminosity and redshift where recently estimated by Band, Norris, and Bonnell (2004) [3] through the use of the empirical lag-luminosity correlation. The statistical techniques we utilize were developed by Lynden-Bell (1979) [4] and Efron and Petrosian (1992) [5] and first applied to GRB analysis by Lloyd-Ronning *et al.*(2002) [6] to measure the underlying luminosity and density distribution in a way that properly accounts for these detection thresholds effects. These techniques work by creating associated sets which include all objects that could have been observed given a certain limiting luminosity, essentially subsets of data which are unaffected by the detector threshold (see fig. 1). We apply the test of independence for truncated data developed by Efron and Petrosian [5] by assuming a simple power law form $g(z) = (1+z)^{\alpha}$

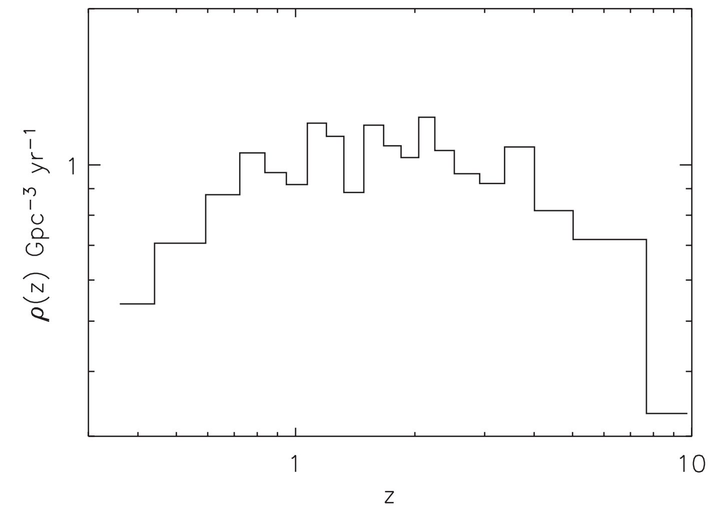

Fig. 2. – The comoving rate density $\rho(z)$ as a function of redshift. The rate density of sources can be seen to increase out to a redshift of 1-2 followed by a flattening before decreasing at higher redshifts. Recent estimates of star formation rates as a function of redshift suggest that the SFR also levels out at high z. The GRB comoving rate density follows (at least qualitatively) this trend. GRBs may allow for a more complete sampling of dust enshrouded star forming regions. The fact that $\rho(z)$ traces the SFR favors short lived progenitors like core collapse SNe over long lived binaries systems. The Rise in the GRB ρz also matches the SNe Ib/c rate density at high redshift measured by Dahlen *et al.*2004. [7]

for the luminosity evolution and then making the transformation $L \to L' = L/g(z)$ and vary α until $\tau \to 0$. Once this parametric form that removes the correlation between L and z is known, it is possible to use Lynden-Bells C-method to estimate the underlying parent luminosity distributions through the equation $\Phi(L_i) = \prod_{k=2}^{j}\left(1 + \frac{1}{N_j}\right)$ Using the alternate definition for the associated set M_j yields the cumulative redshift distribution.

3. – Results

Applying the statistical techniques outlined above, we find a strong (11.63 σ) correlation between luminosity and redshift that can be parameterized as $L(z) = (1+z)^{1.7\pm0.3}$, indicating that the average isotropic GRB luminosity was brighter in the past. The resulting cumulative luminosity function $N(L')$ is well fit by a double power law separated by a break energy at about 10^{52} ergs s^{-1}. We find that the differential luminosity function $\mathrm{d}N/\mathrm{d}L'$ exhibits a power law shape of $L^{-1.5}$ below this break luminosity. The cumulative and differential density functions show a peak in the number of GRBs centered at roughly $z \sim 1$, consistent with current observations. Using the differential density function, we calculate the GRB comoving rate density and find that it increases roughly as $\rho(z) \sim (1+z)^{2.5}$ to a redshift of $z \sim 1$ followed by a flattening and eventual decline above $z > 3$ (see fig. 2). This rate density is in qualitative agreement with recent photometric estimates of the cosmic star-formation rate (SFR), as would be expected if GRBs come from massive short-lived progenitors.

4. – Conclusions

The average isotropic equivalent luminosity of GRBs has evolved with time, being much brighter in the distant past. If the collimation-corrected energy and luminosity are indeed invariant with redshift as suggested by Frial *et al.*(2001) [8] and Bloom *et al.*(2003) [9], it directly implies that the brightening of the apparent isotropic luminosity is actually due to an increase in the beaming factor as a function of redshift and not an increase in the overall energy of the burst. We find no significant evidence for beaming angle evolution in the current sample of GRBs with known redshift, suggesting that the variation of the observed luminosity with redshift cannot be due to an evolution of the collimation angle. Our resulting luminosity function is well fit with a single power law of index $L'^{-1.5}$, which is intermediate between the values predicted by the $k = 2$ power law and Gaussian structured jet models. We find that the GRB comoving rate density rises steeply with a broad peak between $1 < z < 2$ followed by a steady decline above $z > 3$. This rate density qualitatively matches the current estimates of the star formation rate at high redshifts, favoring a short-lived massive star progenitor model, or a binary model with a short delay between the formation of the compact object and the eventual merger.

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