How common are long Gamma-Ray Bursts in the Local Universe?

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ABSTRACT

The two closest Gamma-Ray Bursts so far detected (GRBs 980425 & 060218) were both under-luminous, spectrally soft, long duration bursts with smooth, single-peaked light curves. Only of the order of 100 GRBs have measured redshifts, and there are, for example, 2704 GRBs in the BATSE catalogue alone. It is therefore plausible that other nearby GRBs have been observed but not identified as relatively nearby. Here we search for statistical correlations between BATSE long duration GRBs and galaxy samples with recession velocities $v \leqslant 11,000 \mathrm{km\,s^{-1}}$ ($z = 0.0367, \approx 155$ Mpc) selected from two catalogues of nearby galaxies. We also examine the correlations using burst sub-samples restricted to those with properties similar to the two known nearby bursts. Our results show correlation of the entire long GRB sample to remain consistent with zero out to the highest radii considered whereas a sub-sample selected to be low fluence, spectrally soft, with smooth single-peaked light curves (177 bursts) demonstrates increased correlation with galaxies within ≈ 155 Mpc. The measured correlation ($28\% \pm 16\%$ of the sample) suggests that BATSE observed between 2 and 9 long duration GRBs per year similar to, and from within similar distances to GRBs 980425 and 060218. This implies an observed local rate density (to BATSE limits) of 700 ± 360 $\mathrm{Gpc^{-3}yr^{-1}}$ within 155 Mpc.

Key words: Gamma-Ray Burst

1 INTRODUCTION

The two closest Gamma-Ray Bursts (GRBs) detected so far are GRB 980425 (Galama et al. 1998) and GRB 060218 (Cusumano et al. 2006; Mirabal & Halpern 2006), both long duration GRBs of exceptionally low luminosity. Indeed GRB 980425 is usually taken as the archetypal low-luminosity, low variability, soft spectrum GRB. During nine years of operation, BATSE (the Burst and Transient Source Experiment on board the *Compton Gamma-Ray Observatory*) detected 2704 GRBs. As is well known, there is good evidence for two observed classes of GRB distinguished most clearly by $\mathrm{T_{90}}$, the time taken to collect 90% of a burst's total gamma-ray fluence (Kouveliotou et al. 1993; Norris et al. 1984). Long duration GRBs (L-GRBs, $\mathrm{T_{90}} > 2\mathrm{s}$) show a correlation between spectral peak energy and overall isotropic energy release - the E_p/E_{iso} or Amati relation (Amati et al. 2002)

- where softer bursts are less isotropically energetic (although GRB 980425 is an outlier to this relationship in the sense of being too spectrally hard for its isotropic luminosity, it is still softer than the majority of BATSE long bursts). L-GRBs also exhibit a spectral lag-luminosity relationship (Norris, Marani & Bonnell 2000; Salmonson & Galama 2002; Norris 2002) where there is anti-correlation between overall luminosity and the time delay between the observation of corresponding light curve features in different energy bands. Furthermore, GRBs with long spectral lags (and hence low luminosity) tend to have smoother light curves with broader features, and lower peak fluxes (Norris, Scargle & Bonnell 2001). Isotropic-equivalent peak luminosity has also been shown to correlate with light curve variability, originally for a relatively small number of bursts (Reichart et al. 2001; Fenimore & Ramirez-Ruiz 2000) but recently confirmed by Guidorzi et al. (2005) for a larger sample, though with a larger scatter in the data. Though the exact form and tightness of the correlation is currently a matter of some debate (Reichart & Nysewander 2005;

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Guidorzi et al. 2006; Li & Paczyński 2006), there appears little doubt that the luminosity of long GRBs correlates with variability.

GRBs 980425, 060218 and the next nearest L-GRB with a well observed supernova component to date GRB 031203 (Gotz et al. 2003; Prochaska et al. 2004; Watson et al. 2004) are comprehensively reviewed by Kaneko et al. (2007). The properties of these nearby bursts, along with the correlations discussed above, suggest that under-luminous L-GRBs are likely to be spectrally soft with smooth, single-peaked light curves. Thus we can use these properties to select those bursts most likely to be of intrinsically low luminosity and therefore drawn from a relatively nearby population. Furthermore, as suggested by arguments based on analyses of detector sensitivities and luminosity function calculations (Pian et al. 2006; Soderberg et al. 2006; Liang et al. 2007; Cobb et al. 2006), this sub-class of low-luminosity bursts may be many times more prevalent in the local Universe than high-luminosity bursts.

Approximately 75% of the 2704 BATSE GRBs were long, but due to large localisation error regions few of these bursts have identified hosts or redshifts. However, if some originated within similar distances to GRB 980425 and GRB 060218 then it should be possible to estimate this fraction statistically via their distribution on the sky, using the same technique we used previously to investigate the distribution of short GRBs (Tanvir et al. 2005). If indeed there is an unidentified population of under-luminous, soft, smooth L-GRBs, then restricting the BATSE sample to those with properties similar to GRB 980425 should enhance any correlation signal.

We therefore consider below the correlation between BATSE long bursts and two galaxy catalogues: the PSCz galaxy redshift survey (Saunders et al. 2000) and the Third Reference catalogue of Bright Galaxies (*RC3*) (de Vaucouleurs et al. 1991). The *PSCz* is based on the *IRAS* Point Source catalogue, and is less affected by dust extinction in the galactic plane than other redshift surveys, making it an appropriate comparison dataset for the all-sky BATSE dataset. Though less complete, the *RC3* is useful as a further comparison set and a check against any possible catalogue bias.

2   METHODS

The long burst sample consists of the 1437 long GRBs with location errors $\leqslant 10°$ and measured fluences in the current BATSE catalogue (4B(R) Paciesas et al. (1999), including web supplement). Our galaxy samples are drawn from two galaxy catalogues, the IRAS *PSCz* galaxy redshift survey (Saunders et al. 2000) and the Third Reference Catalogue of Bright Galaxies (*RC3*) (de Vaucouleurs et al. 1991). Using the measured heliocentric recession velocities of galaxies in these catalogues, we made samples of galaxies within concentric spheres of recession velocity $v < 2000, 5000, 8000$ and 11000 km s^{-1} (corresponding to radii of 28($z = 0.0067$),

70(0.017), 113(0.027) and 155(0.037) Mpc respectively)[1]. Following the method described in Tanvir et al. (2005), we define the statistic Φ for each galaxy sample compared with the long GRBs as shown in equation 1, where θ_{ij} is the separation between the ith burst and the jth galaxy, and ϵ_i is the error circle of the ith burst position (statistical combined with systematic errors from model 1 of Briggs et al. (1999)). For each comparison set (burst sample with galaxy sample), Φ thus provides a measure of the overall correlation between the bursts and galaxies.

$$\Phi = \sum_i^{Bursts} \sum_j^{Galaxies} \frac{1}{\epsilon_i} \int_{\theta_{ij}}^{\infty} \frac{1}{\sqrt{2\pi}\epsilon_i} \exp\left[\frac{-\theta^2}{2\epsilon_i^2}\right] d\theta \quad (1)$$

Values of Φ can be calibrated and used to measure the percentage of bursts correlated with each galaxy sample by simulating distributions of known correlation with that galaxy sample. To achieve this we generated a number (501) of distributions of random bursts (each with the same number of positions as the number of bursts under consideration, the same positional errors, and distributed on the sky according to the known BATSE sky exposure map (Hakkila et al. 2003)). From these we computed Φ_0 and its associated dispersion. Similarly, we generated 501 100% correlated test distributions for each galaxy sample (this time with "host" positions chosen randomly from the galaxy sample and pseudo-bursts displaced from these positions assuming Gaussian probability distributions within error circles chosen randomly from the burst sample) which enabled us to calculate Φ_{100}. Calibration plots of Φ/Φ_0 versus percentage correlation with associated errors could then be produced.

To reiterate, the closest known bursts (GRBs 980425, 060218 and 031203) were under-luminous and spectrally soft with smooth single-peaked light curves. In order to select a burst sub-sample with properties similar to these bursts, three separate selections were performed on the L-GRB sample, based on observed fluence, spectral softness, and overall light curve shape. First, as argued above, since long-lag (and therefore likely under-luminous) bursts increase from a negligible proportion of BATSE bright bursts to $\sim 50\%$ at trigger threshold (Norris 2002), we ordered the L-GRBs by total burst fluence and selected the low-fluence half. Similarly, to select for spectrally soft bursts, we split the total sample in half by the ratio of observed fluence in BATSE energy channels 1 ($20 - 50$ keV) and 3 ($100 - 300$ keV). We did not attempt further cuts on the data based on fluence or spectral hardness since this would not be justified for several reasons. Firstly, the number of bursts selected in finer cuts would be very small for statistical analysis. Secondly the low fluence bursts (for example) will obviously contain bursts that are dim due to being further away and these cannot be distinguished from the nearby bursts - we aimed purely to increase the fraction of nearby bursts in the samples as predicted by the correlations guiding the cuts. Thirdly, given the overall lack of

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[1] Throughout this paper we use H$_0$ = 71km s^{-1} Mpc^{-1}. Due to individual peculiar velocities, recession velocity is not always an exact distance proxy.
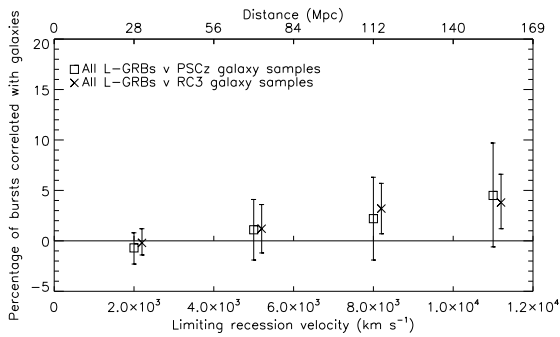
Figure 1. Measured correlation (expressed as the percentage of bursts in each sample correlated with galaxy distribution) versus galactic recession velocity for concentric spheres of galaxy samples. Data points have been separated along the x axis for clarity, and error bars represent 1σ errors.

Figure 2. Measured correlation between BATSE long duration GRBs and galaxies in concentric shells of increasing galactic recession velocity from the *PSCz* catalogue. Details as Figure 1.

Figure 3. Measured correlation between the combined low-fluence, spectrally soft, single-peaked L-GRBs and galaxies in concentric spheres from the *PSCz* catalogue.

correlation in the sample as a whole, any measured correlation is likely to be very weak and further cuts beyond the median would be statistically dubious. The third selection for bursts of a smooth, single-peaked nature was made by visual examination of the light curves of the entire L-GRB sample. We emphasise that this selection was based on simple pre-agreed criteria to select smooth, single peaked curves broadly similar to the known local bursts, not to attempt detailed selection with respect to small scale variation. To further minimise any subjectivity involved, selection was performed independently by two of us and then arbitrated by a third. Finally, the bursts common to all three selections (177) were then used to form a low-fluence, spectrally-soft, single-peaked sub-sample.

3 RESULTS

Figure 1 shows plots of correlation (expressed as the percentage of bursts in each sample correlated with galaxy distribution) between BATSE long GRBs and concentric spheres of galaxy samples from both the *PSCz* and *RC3* catalogues. The results show a high degree of consistency, confirming that the correlation measurements are not dependent on a chance choice of galaxy catalogue. In practice, each volume sample in the *RC3* catalogue contained between 1.5 and 2 times the number of galaxies in the equivalent *PSCz* sample. This inevitably leads to increased dispersion in the values of Φ measured with the *PSCz* samples compared to the *RC3* samples, though we still consider the completeness and homogeneity of the *PSCz* sample to make it a more appropriate comparison set.

As can be seen, long burst correlation (particularly with the *PSCz* samples) remains formally consistent with zero out to the largest radii considered of $v \leqslant 11000$ km s^{-1} (≈ 155 Mpc), confirming that nearby long GRBs are indeed rarely observed events. However, the most probable level of correlation increases with distance, but this could not be reliably investigated beyond the radii considered due to the flux-limited nature of the
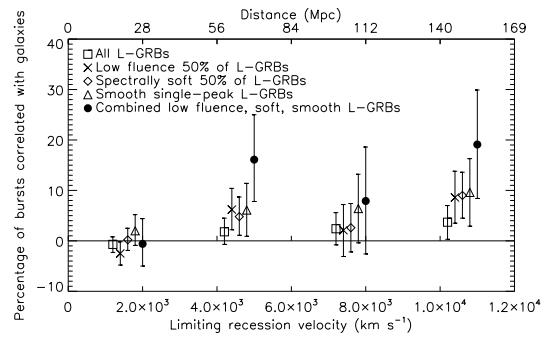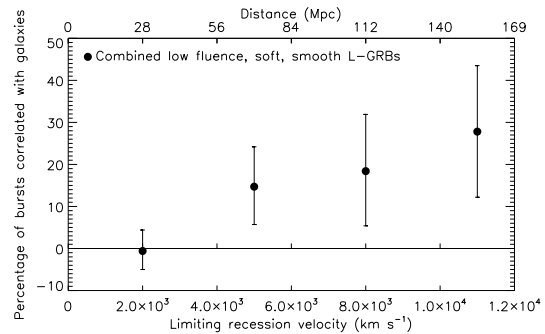
galaxy catalogues meaning that there are just too few galaxies in the catalogues at larger radii to be useful.

Turning now to the sub-samples with properties similar to known local bursts, Figure 2 shows correlations with concentric *shells* (as opposed to *spheres*) of galaxies with recession velocity radii of $0-2000$, $2000-5000$, $5000-8000$ and $8000-11000$ km s^{-1}. From this figure it can be seen that each of the low-fluence, spectrally-soft, and smooth light curve sub-samples exhibits broadly equivalent, marginally increased correlations in the second and fourth shells. Furthermore, a combined set containing only those bursts (177) common to all three individual sub-samples exhibited increased correlation of $16\% \pm 8\%$ ($\equiv 28 \pm 14$ bursts) in the $2000-5000$ km s^{-1} shell, and $19\% \pm 11\%$ ($\equiv 34 \pm 19$ bursts) in the outermost shell.

Returning to examine concentric *spheres* of galaxies, Figure 3 shows the cumulative correlation versus radius of the combined sub-sample of L-GRBs, where it can be seen that $28\% \pm 16\%$ of low-fluence, spectrally-soft bursts with smooth single-peaked light curves are correlated with galaxies within ≈ 155 Mpc, equivalent to a total of 50 ± 28 bursts in the 9 years of BATSE operation.

It is interesting to ask whether our analysis is more sensitive to individual burst/galaxy correlations, or to correlation with large scale structure on the sky. In or-

PSCz galaxy shell recession velocity (km s^{-1})	Φ_{100} incl. host (arbitrary units)	Φ_{100} excl. host (arbitrary units) (%)
$\leqslant$2000	1875	1684 (90%)
2000–5000	2873	2663 (93%)
5000–8000	2354	2151 (91%)
8000–11000	1810	1616 (89%)

Table 1. Values of Φ_{100} for *PSCz* galaxy samples measured including and not including the host of the pseudo-bursts in correlated simulations

der to address this question, we repeated our correlation analyses but this time in calculation of Φ_{100}, for each correlated pseudo-burst we removed the galaxy from which its position was generated. Thus Φ_{100} then measures the correlation between pseudo-bursts and the large scale structure around the generating host. The resulting structure-based Φ_{100} values for the *PSCz* galaxy shells are shown in Table 1.

As this table shows, $\geqslant$ 89% of the correlation signal measured by Φ_{100} is generated from galaxies other than the specific hosts of the pseudo-bursts. It would therefore seem likely that correlation between the real BATSE bursts and galaxy distributions is mainly due to large scale structure on the sky rather than correlation with individual hosts. Given the size of the BATSE error boxes, this is certainly not surprising, but means that our analysis is unlikely to be sensitive to individual galaxy properties. Indeed, analyses performed weighting Φ by estimated individual galactic mass or star formation rate (estimated using the methods described in Levan et al. (2006)), showed no significant change from the unweighted results. However, given the often large error boxes of individual bursts, sensitivity to structure is actually an advantage. Our technique effectively measures the correlation between two 2-dimensional signals, and is statistical in its nature - the signal is produced from the sums of contributions of many burst-galaxy candidate pairs and thus enhances any inherently weak individual correlation measurements at the expense of sensitivity to individual pair properties. This also precludes our ability to identify individual burst/galaxy associations. It is also known that the typical hosts of L-GRBs are blue, faint, irregular galaxies (Fruchter et al. 2006) and thus many potential individual hosts may be missing from the galaxy catalogues.

4   DISCUSSION

4.1   Two populations of long bursts?

Our results confirm that nearby long GRBs as a whole are indeed rare events, with correlation remaining consistent with zero out to $\approx$ 155 Mpc, but with a 10% upper limit (1σ), equivalent to 144 bursts. Restricting the L-GRB sample to those with properties similar to known nearby bursts increased the measured correlation to 28%$\pm$16% of the sub-sample ($\equiv$ 50$\pm$28 bursts) within the same radius. It is worth emphasising that this means
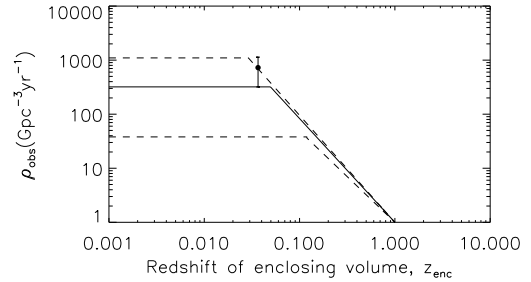

Figure 4. The observed burst rate, ρ_{obs}, within the enclosed volume out to redshift z_{enc}. The filled circle shows the observed burst rate within our investigated total volume. The area enclosed by the dashed lines represents the upper and lower limits of the predicted observed rate for Low-Luminosity GRBs as a function of enclosing volume (after Figure 5(b) of Liang et al. (2007)).

the 177 burst sub-sample contains a *lower* limit (1σ) of 22 bursts correlated with local large scale structure, almost one quarter more than the 1σ *upper* limit (18) expected from the correlation rate of the sample as a whole. The local rate density of under-luminous L-GRBs implied by our result is in agreement with those calculated via detector sensitivity and luminosity function arguments. For example, Soderberg et al. (2006) argue that sub-energetic bursts are 10 times more abundant than typical bright GRBs based on the sensitivities of *BeppoSAX*, *HETE-2* and *Swift* to GRB 980425 and GRB 060218, and similarly Pian et al. (2006) (using BATSE, *HETE-2* and *Swift* sensitivities) found a local rate density at least 100 times greater than that estimated from cosmological bursts alone. In addition Cobb et al. (2006) estimate an event ratio $\sim 10^2$ between low and high luminosity bursts based on assuming the *Swift* population of high-luminosity bursts to be complete to its mean redshift. Furthermore, Liang et al. (2007) suggest that in order to avoid over-predicting the number of intermediate luminosity GRBs observed at low redshifts, the high-luminosity and low-luminosity bursts must be characterised by separate luminosity functions. They choose models of the same functional form (smoothed broken power-law), but with the coefficients of each separately constrained to produce GRB rates consistent with those observed. Finally, Guetta & Della Valle (2007) estimate a local GRB rate of $200 - 1800 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ using a luminosity function consistent with the luminosities of local bursts. Figure 4 shows our results plotted with respect to predicted rates of Low-Luminosity GRBs from Liang et al. (2007). The results presented here can be seen to provide independent confirmation of these luminosity function based predictions.

4.2   Comparison with supernova searches

GRB 980425 was the first GRB to be observationally associated with a supernova (Galama et al. 1998), and GRB 060218 (Cusumano et al. 2006) is the most strik-

ing recent example. These nearby SN associated L-GRBs share similar properties (low-fluence, spectrally soft and smooth single-peaked light curves) as argued by Bloom et al. (1998), and it may therefore seem that a search for temporal and spatial correlation between bursts and supernovae would provide a means of identifying individual GRB hosts, particularly at low redshift. However the heterogeneity and inherent incompleteness of SN catalogues (due for example to the difficulty of SN detection in dusty environments, biased surveys and magnitude limitations) make it difficult to use them to identify GRB host galaxies. Recent observations also suggest that not all long GRBs are necessarily accompanied by an observable supernova (Fynbo et al. 2006; Gal-Yam et al. 2006; Della Valle et al. 2006), and of course, not all Ib/c SNe produce GRBs (e.g. Soderberg et al. (2006)). Nevertheless several groups have attempted searches for spatial and temporal coincidences of GRBs with SNe (for example Wang & Wheeler (1998); Kippen et al. (1998); Norris, Bonnell & Watanabe (1999)). Results obtained vary depending particularly on any restrictions imposed on the burst or SN properties in the analyses, and generally the statistics remain too poor to draw any firm conclusions from these and other studies. In addition, it has been suggested recently that the host galaxies of SNe type Ic without GRBs may be systematically different from those with GRBs, particularly in terms of metallicity (Modjaz et al. 2007).

It is therefore apparent that using SNe searches to identify possible nearby GRBs is fraught with difficulty. Soderberg et al. (2006) estimate that only $\sim 3\%$ of Ib/c SNe give rise to detectable low-luminosity GRBs comparable to GRBs 980425 and 060218. During the lifetime of the BATSE experiment, the Asiago supernova catalogue (Barbon et al. 1999)[2] contains only 33 events classified as Ib, Ibc or Ic within the volume considered here. Given further that most supernova searches, particularly in the 1990s, concentrated on targetting relatively bright galaxies, untypical of GRB hosts, we should expect that few, if any, GRB-SN were discovered by chance in these surveys. Our approach, independent of any assumed correlation other than that GRBs must occur in or near a host galaxy, is therefore justified and enables the placing of limits to the number of observed nearby L-GRBs based on location with respect to potential host galaxy distributions alone.

5 SUMMARY AND CONCLUSIONS

We have analysed the correlations of the entire BATSE catalogue of long GRBs with measured fluences localised to better than $10°$ (1437 bursts) with galaxy samples out to ≈ 155 Mpc from two independent galaxy catalogues. We find that correlation between the L-GRB set as a whole and samples from both galaxy catalogues remains within 1 standard deviation (σ) of zero out to the highest radii considered. However, selecting a sub-sample of

bursts with properties similar to those of the known local L-GRBs significantly increased correlation with large scale structure on the sky to a level of $28\% \pm 16\%$ ($\equiv 50 \pm 28$ bursts) within the same radius.

The cumulative correlation rate out to ≈ 155 Mpc suggests that BATSE most likely observed between 2 and 9 long GRBs per year similar to, and from within similar distances to the closest known GRBs to date. This implies an observed local L-GRB rate density within 155 Mpc of 700 ± 360 Gpc^{-3}yr^{-1} (to BATSE detection limits, and assuming the BATSE sky exposure fraction to be of the order of 0.5). This is in reasonable agreement with 230^{+490}_{-190} Gpc^{-3}yr^{-1} as calculated by Soderberg et al. (2006) via combined analyses of the sensitivities of *BeppoSAX*, *HETE II*, *Swift*. It is also in very good agreement with observed rates of Low-Luminosity GRBs predicted from luminosity function arguments (Liang et al. 2007; Guetta & Della Valle 2007).

At the time of writing (March 2007) ≈ 50 *Swift*-detected long duration GRBs have measured redshifts out of a total of ≈ 180 detections. The mean redshift of an unbiased sample of 16 *Swift* long GRBs measured in late 2005 was $z = 2.8$ (Jakobsson et al. 2006), though the highest so far is $z = 6.295$ (Haislip et al. 2006; Kawai et al. 2006) and the lowest GRB 060218 with $z = 0.0331$. Comparison between datasets from different missions and detectors is difficult (see for example Berger et al. (2005); Band (2006)). However if we naively assume the *Swift* GRB catalogue to be similar to the BATSE catalogue, then in a sample of 50 bursts we would expect to find between 0 and 5 within 155Mpc, as is the case. It may be argued that since we are looking for nearby bursts, these would be more likely to have measured redshifts than the bursts in general, though all three nearest GRBs were significantly underluminous events. Even so, comparing to the entire *Swift* sample of 180 long GRBs, our results suggest it contains 9 ± 9 bursts with redshift less than 0.0367. So far, only one has been identified as occurring within our considered volume: GRB 060218. This is certainly consistent with our limits (particularly given the relatively small numbers involved), but we may expect more low-redshift long bursts to be identified in the future, particularly among spectrally-soft, under-luminous bursts with little variability.

6 ACKNOWLEDGEMENTS

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