ON THE GALACTIC DISTRIBUTION OF GAMMA-RAY BURSTS

ROBERT E. RUTLEDGE AND WALTER H. G. LEWIN

Center for Space Research and Department of Physics
Massachusetts Institute of Technology, Room 37-627, Cambridge, MA 02139, USA
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Abstract

Recently, Quashnock and Lamb 1993 (hereafter QL) defined a sub-sample of Gamma-ray Bursts (GRBs) from the publicly available BATSE database which shows clumping toward the galactic plane, and they concluded that all GRBs are galactic in origin. The selection of these bursts (duplicated in this work in Sample 1) involved a peak count-rate (in counts/s) which is uncorrected for aspect. Using, as limits, the corresponding peak fluxes (in photons/cm² s) for the bursts in the QL sample, we find an additional 24 bursts, which we include in a new sample (Sample 2). We assert that the peak flux of a burst – the peak count-rate corrected for detector aspect and energy response – is physically more meaningful than peak count-rate, as used by QL. We find that the significance of anisotropy in Sample 2 is much less than that of Sample 1, which does not support QL’s interpretation of the anisotropies as being due to a galactic population.

In addition, to make meaningful statistical statements regarding isotropy, burst samples must have peak fluxes above a minimum flux, which is set by the requirement that a burst of certain flux be detectable from any direction (above the horizon) with respect to GRO, at any detection threshold at which a burst was observed in that sample. We split our Sample 2 into two sub-samples on this basis (Sample 3 and Sample 4, which have fluxes below and above, respectively, this minimum flux). We find that Sample 4 has a marginal (2.6σ) deviation from isotropy, which we consider insufficient to justify the claim that GRBs are galactic in origin.

Subject headings: gamma rays; bursts

1 Introduction

Quashnock and Lamb 1993 (hereafter QL) define a sample of bursts using two parameters which they derive from data in the publicly available BATSE database (Fishman et al. 1993): V (which indicates short-time scale variability) and B, which they call burst peak brightness. Both of these values are found using the CMAX/CMIN Table available from the BATSE public catalog. The CMAX/CMIN Table includes values of $C_{\text{max}}^t/C_{\text{min}}^t$, which is the ratio of peak count-rate ($C_{\text{max}}^t$, in counts/t ms) in a time bin of duration t ms to the burst trigger threshold $C_{\text{min}}^t$ (in counts/t ms) for the time bin of duration t ms. It also includes values of $C_{\text{min}}^t$, so $C_{\text{max}}^t$ can be found. These values are available for $t = 64, 256$, and 1024 ms.

The “variability” parameter V (see Lamb, Graziani, & Smith 1993; however, see also Rutledge and Lewin 1993) is defined:

$$V = \frac{C_{\text{max}}^{64}}{C_{\text{max}}^{1024}}$$

(1)

and the “brightness” parameter B is simply the maximum peak counts in a 1024 ms bin observed during the burst ($C_{\text{max}}^{1024}$). Thus, the brightness B has the units of counts/1024 ms. QL use these parameters to select their sample of bursts. They find that, for the sample of bursts of log(V)< -0.8 (corrected for “Meegan’s Bias”; see Lamb, Graziani, & Smith 1993) and 465 ≤ B ≤ 1169, the bursts are significantly clumped (~ 4.8σ equivalent Gaussian standard deviations) toward the galactic plane, with a value $< \cos l >= 0.230 \pm 0.078$ and $< \sin^2 b > = -\frac{1}{3} = -0.119 \pm 0.040$. 

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In the following discussion and throughout this work, when we mention peak flux, we mean the maximum 1024 ms averaged flux value, in $\text{photons cm}^{-2} \text{s}^{-1}$, measured during a burst.

The reader will appreciate that $B$ is a count-rate *uncorrected for aspect*; it is not a flux. This means that, if a given population of bursts had identical peak fluxes, $B$ could vary appreciably depending on the orientation of the Compton Observatory. In actuality, we find that the proportionality of $B$ (in counts/1024ms) to $I_{\text{peak}}^{1024}$ (found in the publicly available BATSE catalog Flux tables, in $\text{photons cm}^{-2} \text{s}^{-1}$) can be different by a factor of up to $\sim 3$, with 68% of the values to be within 27% of the mean (see Figure 1). Simply put, this means that a burst with a given flux (in $\text{photons cm}^{-2} \text{s}^{-1}$) could produce values of $B$ which differ by up to a factor of 3, and routinely by a factor of 1.6, due to the orientation of the Compton Observatory.

The BATSE catalog $B$ values come only from the *second* most brightly illuminated BATSE detector, which, at best, could have its normal directed $\sim 35^\circ$ or, at worst, as much as $70^\circ$ from the burst direction. Since the angular resolution of a single BATSE Large Area Detector is similar to $\cos \theta$ (flatter for energies $> 300$ keV; Fishman et al. 1989), it is evident that aspect can cause significantly different values of $B$ to be obtained for bursts of identical peak flux, due only to the orientation of the Compton Observatory.

Clearly, use of $B$ as a criterion for a burst population study opens up the possibility of a directionality bias. This can be overcome by setting a lower limit on the peak flux ($I_{\text{peak}, LL}^{1024}$) on the bursts included, such that at all times it is possible to detect a burst with peak flux $I_{\text{peak}}^{1024}$ from any unoccluded direction.

$I_{\text{peak}, LL}^{1024}$ can be roughly approximated using data from the public BATSE database. Assume a burst with peak flux $I_{\text{peak}}^{1024}$ is incident on the BATSE detectors from a direction with transmission efficiency $\alpha$, approximated by:

$$\alpha I_{\text{peak}}^{1024} = B = \frac{C_{\text{max}}^{1024}}{C_{\text{min}}^{1024}} C_{\text{min}}^{1024}$$

where $B$ is in counts/1024ms, $I_{\text{peak}}^{1024}$ is in $\text{photons cm}^{-2} \text{s}^{-1}$, and we’ve included the time proportionality (1 sec/1024ms) in $\alpha$. If $I_{\text{peak}, LL}^{1024}$ is to be minimally detectable (i.e., $C_{\text{max}}^{1024} / C_{\text{min}}^{1024} = 1.0$), from any unoccluded angle (that is, at the lowest possible $\alpha$) at any time (when the detection threshold $C_{\text{min}}^{1024}$ is highest), then we find:

$$I_{\text{peak}, LL}^{1024} = \frac{\text{MAX}(C_{\text{min}}^{1024})}{\text{MIN}(\alpha)}$$

where $\text{MAX}(C_{\text{min}}^{1024})$ is the maximum of all values $C_{\text{min}}^{1024}$ for bursts considered and $\text{MIN}(\alpha)$ is the minimum of all values of $\alpha$. We here make the assumption that the 207 bursts in the public database for which $\alpha$ values can be found have more or less explored the unoccluded aspect-space of BATSE. Using data from the database, we find $\text{MAX}(C_{\text{min}}^{1024}) = 346$, $1/\text{MIN}(\alpha) = 0.001948$, (where we have ignored one exceptionally high value of $1/\alpha$, from burst number 1346, for which the $(C_{\text{min}}^{1024})_{\text{max}}$ value listed in the BATSE public database is probably erroneous; see Lamb, Graziani, & Smith 1993), and therefore our $I_{\text{peak}, LL}^{1024}=0.674$ $\text{photons cm}^{-2} \text{s}^{-1}$. There are 104 bursts in the public database above this flux limit (i.e. which could have been detected from any unoccluded direction at any time during the BATSE observation period) for which $\alpha$ can be found. If each has a systematic positional error box of $4^\circ$ which does not overlap with another in aspect-space, then the aspect space would be 101% filled. The assumption that the aspect space is completely explored is therefore, perhaps, not unreasonable.

It is possible to limit the sample of our bursts to those detected at times with lower background, and thus find a lower $\text{MAX}(C_{\text{min}}^{1024})$, which would lower the $I_{\text{peak}, LL}^{1024}$ as well. However, to calculate the significance of any such result, we require knowledge of the Sky Exposure during which $C_{\text{min}}^{1024} \leq \text{MAX}(C_{\text{min}}^{1024})$, and as the public database currently lists only the complete Sky Exposure, we must take the highest $C_{\text{min}}^{1024}$ observed, producing the subsequently higher $I_{\text{peak}, LL}^{1024}$. 


2 Analysis

We defined four burst samples, described below and shown in Figure 2a as a function of \( B \) and burst peak flux. The two vertical lines in this figure are the \( \text{Cr}^{1024} \) limits used by QL. The two solid horizontal lines are the second highest and second lowest peak fluxes in the sample defined by QL, and the broken horizontal line is \( I_{\text{peak, LL}}^{1024} \). We use these fluxes in the definitions of Samples 2, 3, & 4:

**Sample 1.** Sample 1 (shown in Figure 2a) is identical to the burst sample used by QL. Using the \( B \) and \( V \) values kindly provided (Carlo Graziani, private communication), bursts were selected which had 465 \( \leq \) \( B \leq \) 1169 \( \text{count s}^{-1} \), and \( \log(V) \leq 0.8 \). There are 55 bursts which meet these criteria.

**Sample 2.** Sample 2 (Figure 2b) includes bursts with peak fluxes \( 0.396 \leq I_{\text{peak}} \leq 1.296 \) \( \text{photons cm}^{-2} \text{s}^{-1} \), with \( \theta_{\text{pos}} \leq 10^\circ.77 \), and with \( \log(V) \leq 0.8 \). \( \theta_{\text{pos}} \) is the total positional error box. We find 79 bursts meeting these criteria.

**Sample 3.** Sample 3 (Figure 2c) includes bursts with peak fluxes \( 0.396 \leq I_{\text{peak}} \leq 0.674 \) \( \text{photons cm}^{-2} \text{s}^{-1} \), with \( \theta_{\text{pos}} \leq 10^\circ.77 \), and with \( \log(V) \leq 0.8 \). Sample 3 is a subset of Sample 2. We find 40 bursts meeting these criteria.

**Sample 4.** Sample 4 (Figure 2d) includes bursts with peak fluxes \( 0.674 \leq I_{\text{peak}} \leq 1.296 \) \( \text{photons cm}^{-2} \text{s}^{-1} \), with \( \theta_{\text{pos}} \leq 10^\circ.77 \), and with \( \log(V) \leq 0.8 \). Here we have used the \( I_{\text{peak, LL}}^{1024} \) found above as our lower flux limit. We find 39 bursts meeting this criteria. Sample 4 is a subset of Sample 2, and is complimentary to Sample 3.

Figure 3 shows positional mappings in Galactic coordinates of each of the four samples.

Using the Galactic positions of each burst, we produce values of \( < \cos \ l > \) and \( < \sin^2 b > \ - \frac{1}{3} \) for each of the four samples.

3 Results

The results of this analysis are shown in Table 1, along with the result of the analysis performed by QL. Due to unequal sky coverage, the standard deviations quoted in the \( < \cos \ l > \) and \( < \sin^2 b > \ - \frac{1}{3} \) columns are not Gaussian, although because the sky coverage is not enormously uneven (i.e. varies by \( \sim 40\% \)), the standard deviations can be taken to be very roughly of Gaussian significance.

Sample 1, selected using identical criteria to QL, produces a value of \( < \cos \ l > \) and which is different from that found by QL although it is identical in significance \((+0.272 \pm 0.093 \text{ vs.} +0.230 \pm 0.078; \text{both} \ 2.9\sigma)\). The values of \( < \cos \ l > \) and its uncertainty are both larger than those found by QL by a factor of \( \approx 1.18 \), which is roughly \( 2\sigma \). The value of \( < \sin^2 b > \ - \frac{1}{3} \) is identical to that found by QL, although the significance we find is greater than that found by QL \((-0.119 \pm 0.030, \text{ vs.} \ 0.040, \text{which is} \ 4.0\sigma \text{ vs.} \ 3.0\sigma)\).

Sample 2, selected using the more physically meaningful flux limits similar to those which exist in Sample 1, produces values of \( < \cos \ l > \) and \( < \sin^2 b > \ - \frac{1}{3} \) with considerably lower significance than Sample 1 \((1.8\sigma \text{ and} 2.4\sigma, \text{respectively})\).

Sample 3, composed of bursts from Sample 2 which have \( I_{\text{peak}}^{1024} < I_{\text{peak, LL}}^{1024} \), produces a stronger dipole \((2.1\sigma)\) than Sample 2, but no significant quadrupole \((0.8\sigma)\).

Sample 4, composed of bursts from Sample 2 which have \( I_{\text{peak}}^{1024} > I_{\text{peak, LL}}^{1024} \), produces a stronger quadrupole \((3.0\sigma)\) than Sample 2, but no significant dipole \((0.5\sigma)\).

QL quantify the significance of their result through Monte Carlo simulations to find the probability of producing their observed dipole and quadrupole moments from an isotropic distribution, correcting for sky coverage. However, the Sky Exposure Table of the BATSE public database states that the Sky Exposure
values apply “to bursts intense enough to trigger the instrument from any direction not occulted by the earth,” (that is, for bursts with \( I_{\text{peak}} \geq I_{\text{peak,LL}} \), \( t=64, 256, \) or \( 1024 \)ms). We find that approximately one third of the bursts in the QL sample do not meet this criterion; had the Compton Observatory been pointed in a different direction, or had they occurred during periods of higher background, these bursts may not have been detected by BATSE. Because QL used the Sky Exposure Table to calculate the probability of detecting bursts which the Sky Exposure Table excludes, the probabilities QL derives using the Sky Exposure Table may not apply. The same is true for our Samples 1, 2 & 3; the probabilities for the deviations from isotropy in these samples cannot be calculated in a straightforward manner.

We performed Monte Carlo simulations (see Appendix A) to find the significance of the deviations from isotropy found in Sample 4, which is composed entirely of bursts with \( I_{\text{peak}}^{1024} \geq I_{\text{peak}}^{1024,\text{LL}} \). We note that none of the 39 bursts from Sample 4 were “overwrites” – bursts which triggered the BATSE detectors prior to the readout period of an earlier, weaker burst; these cannot be used in conjunction with the Sky Exposure Table, as they occur during detector “dead-time”.

Taking into account sky coverage, we find a probability of producing equal or greater \( < \cos l > \) and \( < \sin^2 b > -\frac{1}{3} \) terms as in Sample 4 to be 0.90\% (\( =2.6\sigma \), see Appendix A).

4 Discussion and Conclusions

We find that the sample of BATSE bursts used by QL does not constitute a flux-selected sample, but is based on the (physically irrelevant) pointing of the GRO satellite.

We also find that a sample of BATSE detected bursts will be directionally biased if steps are not taken to insure that all bursts within a defined sample were detectable at the highest detection threshold limit (i.e. for the highest value of \( C_{\text{min}} \) used within the sample and for all aspect angles. We point out that with a more exact knowledge of the angular response, \( I_{\text{peak}}^{1024} \) could be more precisely defined than we have done so here.

In going from a “brightness”-selected sample (Sample 1) to a flux-selected sample (Sample 2) within the flux limits of the “brightness” sample, we find that the non-Gaussian significances of \( < \cos l > \) and \( < \sin^2 b > -\frac{1}{3} \) drop considerably (from 2.9\sigma and 4.0\sigma, to 1.8\sigma and 2.4\sigma). This does not support QL’s interpretation of an anisotropy in the GRB distribution as due to a galactic origin. Because the flux limits used in this sample include bursts with fluxes well below the flux completion limits of the BATSE database, it is not straightforward to estimate significances of this measurement in the absence of directionally specific (i.e., RA and dec.) flux-detection efficiencies.

While the probability of producing the observed anisotropies from a purely isotropic distribution of bursts on the sky is small (0.9\%), we feel that it is not small enough to justify the claim that GRBs are of galactic origin.

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Note added in proof: It was announced at the Hunstville Gamma Ray Burst Workshop 1993 by C. Meegan that bursts selected in the brightness range \( 490 < B < 1250 \) from 480 bursts observed by BATSE not included in the first BATSE GRB catalog have no significant deviation from an angularly isotropic distribution. This is in support of our conclusions.
We have contacted C. Kouveliotou and G. Pendleton regarding uncertainties in the BATSE flux values in the first BATSE catalog. The upper limits on systematic errors in the peak fluxes are 10-15 per cent, which is much lower than the known systematic errors, due to angular response, in peak counts as used by as QL.

REFERENCES


Appendix A: Monte Carlo Simulations

We outline the Monte Carlo simulations used to determine the significance of the deviations from isotropy.

We have a burst sample of N bursts with observed values of $< \cos l >_{\text{obs}}$ and $(< \sin^2 b >_{\text{obs}}, -1/3)_{\text{obs}}$.

We perform a simulation, placing N bursts randomly on the sky in RA and Declination, $\alpha_i$ and $\delta_i$ with angles (for the $i^{th}$ burst):

$$\alpha_i = 2\pi X$$
$$\delta_i = \arccos(1 - 2Y) - \frac{\pi}{2}$$

where $X$ and $Y$ are random uniform deviates between 0 and 1, inclusive (using a random number generator from Press et al., 1988), and $1 \leq i \leq N$. We then look up the total exposure time ($E_i$) for $\delta_i$ in the BATSE Sky Exposure Table. We transform from RA/DEC to Galactic co-ordinates ($\alpha_i$, $\delta_i$ to $b_i$, $\ell_i$), and find the values for the simulated sample of bursts:

$$< \cos l > = \frac{\sum_{i=1}^{N} E_i \cos(\ell_i)}{\sum_{i=1}^{N} E_i}$$
$$< \sin^2 b > = \frac{\sum_{i=1}^{N} E_i \sin^2(b_i)}{\sum_{i=1}^{N} E_i}$$

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We perform this simulation of N bursts continually, keeping a tally of $N_{\text{trials}}$ (the number of N-burst simulations) and $N_{\text{success}}$, which is incremented when the following criteria are met:

\[
\begin{align*}
| \cos l | & \geq | \cos l_{\text{obs}} | \\
\sin^2 b & \leq \sin^2 b_{\text{obs}}
\end{align*}
\]

since we are interested only in matching or exceeding the magnitude (not the sign) of the dipole, and since we must also match or exceed the quadrupole. When $N_{\text{success}}$ is large (>3000), we stop the simulations, and take the probability of matching or exceeding the observed Galactic dipole and quadrupole

\[
Q = \frac{N_{\text{success}}}{N_{\text{trials}}}
\]

We then look up the corresponding tabulated Gaussian standard deviation value in Bevington (1969) which encompasses $1 - Q$ of all values. For instance, if $Q = 0.32$, then 1 Gaussian standard deviation encompasses $1-0.32=0.68$ of all measured values. We call this this an “equivalent Gaussian standard deviation” of $1\sigma$. 

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### Table 1: Results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Flux Limits (photons cm⁻² s⁻¹)</th>
<th>Number of Bursts</th>
<th>&lt; cos l &gt;&lt;sup&gt;a&lt;/sup&gt;</th>
<th>&lt; sin² b &gt; - ½&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>QL Result</td>
<td>-</td>
<td>55</td>
<td>+0.230 ± 0.078 (2.9σ)</td>
<td>-0.119 ± 0.040 (3.0σ)</td>
<td>-&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>55</td>
<td>+0.272 ± 0.093 (2.9σ)</td>
<td>-0.119 ± 0.030 (4.0σ)</td>
<td>-&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>2</td>
<td>0.396 ≤ L&lt;sub&gt;peak&lt;/sub&gt; ≤ 1.296</td>
<td>79</td>
<td>+0.141 ± 0.077 (1.8σ)</td>
<td>-0.070 ± 0.029 (2.4σ)</td>
<td>-&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>3</td>
<td>0.396 ≤ L&lt;sub&gt;peak&lt;/sub&gt; ≤ 0.674</td>
<td>40</td>
<td>+0.233 ± 0.111 (2.1σ)</td>
<td>-0.035 ± 0.047 (0.8σ)</td>
<td>-&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>4</td>
<td>0.674 ≤ L&lt;sub&gt;peak&lt;/sub&gt; ≤ 1.296</td>
<td>39</td>
<td>+0.048 ± 0.104 (0.5σ)</td>
<td>-0.106 ± 0.035 (3.0σ)</td>
<td>0.0090</td>
</tr>
</tbody>
</table>

<sup>a</sup> Standard deviations given parenthetically are only roughly Gaussian (see text)

<sup>b</sup> Probabilities not calculated (see text)
Figure 1: Ratio of $B$ to $I_{\text{peak}}^{1024}$ for bursts in the BATSE public database. This ratio is identical to the $\alpha$ we use in Equation 2.

Figure 2: Peak Flux (in photons/cm$^2$/sec) (from the flux tables of the BATSE public database) vs. brightness $B(= C_{\text{max}}^{1024} / C_{\text{min}}^{1024} \ast C_{\text{min}}^{1024}$, both from the CMAX.CMIN table of the BATSE public database). The two vertical lines are the $C_{\text{max}}^{1024}$ limits used by QL. The two horizontal bars are the second highest peak fluxes in the sample defined by QL. (a) Bursts selected into Sample 1, following the criterion of QL. (b) Sample 2 bursts. (c) Sample 3 bursts. Sample 3 is a subset of Sample 2. (d) Sample 4 bursts. Sample 4 is a subset of Sample 2, and is complimentary to Sample 3.

Figure 3: Projection mappings of four samples of GRBs for the present work, in galactic coordinates. The sample number is indicated above each panel.