EVIDENCE FOR BRIGHTNESS-DEPENDENT ANISOTROPY OF GAMMA RAY BURSTS AND ITS GALACTIC INTERPRETATION

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We show that the brighter gamma-ray bursts (GRBs) in the BATSE 3B catalog concentrate slightly toward the Galactic plane and center, suggesting that at least some bursts originate within the Galaxy. To develop an interpretation of this brightness-dependent anisotropy, we consider GRBs distributed in a thick disk centered on the Galaxy. As an approximation to the true luminosity distribution, we divide bursts into two distinct luminosity classes. Most bursts originate from low-luminosity, nearby sources while the relatively few high-luminosity sources trace the shape of the thick disk. We find that characteristic disk dimensions as small as 20 kpc in thickness and 30 kpc in radial extent can match the observed brightness-dependent anisotropy as well as the number-flux distribution; these dimensions are smaller than previously considered viable. For bursts distributed in a disk of these compact dimensions, the low-luminosity sources must have peak powers of $\lesssim 5 \times 10^{40}$ erg s$^{-1}$ and rate densities of $\gtrsim 5 \times 10^{-3}$ yr$^{-1}$ kpc$^{-3}$. The high-luminosity sources must have a peak luminosity of $\simeq 10^{42}$ erg s$^{-1}$ but their rate density need be only 5% or less than that of the low-luminosity sources. If the Andromeda Galaxy contained a similar population of high-luminosity sources, their peak gamma-ray fluxes would be less than $\sim 0.1$ s$^{-1}$ cm$^{-2}$, making their detection problematic. Statistical analyses of the gamma-ray burst events obtained since the compilation of the 3B catalog will determine whether the thick-disk interpretation is preferred over the isotropic one.
1. INTRODUCTION

The 3B catalog (Meegan et al. 1996) of gamma ray bursts (GRBs) of the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory shows that the overall burst distribution is highly isotropic, suggesting a cosmological origin. The mean values of the Galactic quadrupole and dipole moments of this burst distribution are consistent, within better than one standard deviation, with the events being isotropic on the sky. These statistics, however, are strongly weighted by the numerous faint GRBs not much brighter than the detection threshold. The overall isotropy does not preclude the possibility that GRB subsets exhibit anisotropy, which would be indicative of a Galactic origin. Atteia & Dezalay (1993) present evidence for brightness-dependent anisotropy, and the study of Briggs et al. (1996) shows hints of such a correlation.

Brightness-dependent anisotropy would arise if GRBs originated from a Galactic distribution of sources, occurring with a range of luminosities. The bursters of lowest luminosity would be detected from relatively near the sun and could generate the numerous, faint isotropic events. The high-luminosity ones could be visible at the extremities of the galaxy and appear as anisotropic bright events. Equivalently, there could be one class of bursters whose emission is strongly beamed so that the bursters are faint when viewed from most directions but bright when viewed along the beam. Mao & Paczyński (1992), Higdon & Lingenfelter (1992), Smith & Lamb (1993) and Smith (1995) have investigated two-luminosity class Galactic GRB models.

In this Letter we describe the observational evidence for brightness-dependent anisotropy and construct two-component Galactic models which are consistent with the observations. We show that brighter bursts in the BATSE 3B catalog tend to concentrate toward the Galactic plane, and to a lesser extent toward the Galactic center. We then develop a class of thick-disk models which match the angular data, as well as the observed
number of bursts per peak flux interval.

2. DATA ANALYSIS

The BATSE 3B catalog contains data for 1122 GRBs. To search for brightness-dependent anisotropy we use the subset of 847 bursts for which both peak fluxes and positions have been determined. For this sample we evaluate the cumulative Galactic dipole and quadrupole moments:

\[
\langle \cos \theta \rangle_P = \frac{1}{N_P} \sum_{P_i \geq P} \cos \theta_i, \\
\langle \sin^2 b - \frac{1}{3} \rangle_P = \frac{1}{N_P} \sum_{P_i \geq P} (\sin^2 b_i - \frac{1}{3}).
\]

In these expressions \(P_i\) is the peak number flux of the \(i\)th burst, \(b_i\) is its Galactic latitude, and \(\theta_i\) is the angle between the event and the Galactic center. The averages are taken over the \(N_P\) bursts with peak fluxes of \(P\) or greater.

The jagged solid lines in Fig. 1 show the cumulative dipole and quadrupole moments as functions of peak flux. The peak fluxes were measured at 64 ms resolution. For an isotropic distribution of events, both moments would be zero. However, because the BATSE sky coverage was uneven, the expected values of the moments for an isotropic distribution are \(\langle \cos \theta \rangle_{iso} = -0.013\) and \(\langle \sin^2 b - \frac{1}{3} \rangle_{iso} = -0.005\) [Meegan et al. 1996]. These expected values are indicated by the solid horizontal lines. The positive values of the cumulative dipole moment for the brighter gamma-ray bursts suggest that these events are somewhat clustered in the direction of the Galactic center, while the negative values of the cumulative quadrupole moment for the brighter events indicate a preference for the Galactic plane.

To assess the significance of the observed deviations from the isotropic values, we compute the statistical residuals, \(\chi_D\) and \(\chi_Q\), for the dipole and quadrupole moments,
defined as

\[ \chi_D \equiv \left[ \langle \cos \theta \rangle_P - \langle \cos \theta \rangle_{\text{iso}} \right]/\sigma_D, \]  

\[ \chi_Q \equiv \left[ (\sin^2 b)_P - (\sin^2 b)_{\text{iso}} \right]/\sigma_Q, \]

where the \( \sigma_i \) are the standard deviations. For a sample of \( N_P \) isotropically distributed bursts, the standard deviations are \( \sigma_D = \sqrt{1/3N_P} \) and \( \sigma_Q = \sqrt{4/45N_P} \). The solid lines in Fig. 2 show the statistical residuals between the BATSE data and an isotropic source distribution. The magnitude of \( \chi_Q \) exceeds unity for peak fluxes below \( \sim 15 \text{ s}^{-1} \text{ cm}^{-2} \), and it reaches \( \sim 3 \) at \( P \sim 5 \text{ s}^{-1} \text{ cm}^{-2} \). This concentration of bright bursts toward the Galactic plane suggests, but does not prove, that the isotropic interpretation is inadequate. The evidence for a concentration in the direction of the Galactic center is not as strong. The values of \( \chi_D \) exceed unity for peak fluxes between \( P \sim 4 \) and \( 15 \text{ s}^{-1} \text{ cm}^{-2} \), but do not go beyond \( \sim 2 \) for any flux. Figure 3 shows the differential distribution, \( dN_P/d\ln P \). The deviation from a slope of \(-3/2\) below a peak flux of \( \sim 10 \text{ s}^{-1} \text{ cm}^{-2} \) suggests inhomogeneity in the source distribution. Below a peak flux of \( \sim 1.5 \text{ s}^{-1} \text{ cm}^{-2} \), the effects of detector efficiency become significant.

### 3. CALCULATIONS

To illustrate that a galactic interpretation of GRBs is consistent with the observed angular and flux distributions, we consider GRBs distributed in a thick disk centered on the Galaxy. As an approximation to the true luminosity distribution, we divide bursts into two distinct classes with luminosities \( L_1 \) and \( L_2 \) \((L_1 > L_2)\). The GRB rate-densities, \( \dot{n}_i \) (yr\(^{-1}\) kpc\(^{-3}\)), are represented by an oblate ellipsoid with a Gaussian profile:

\[ \dot{n}_i = \dot{N}_i \exp \left[ -\frac{1}{2} \left( \frac{\rho}{H_{\rho}} \right)^2 - \frac{1}{2} \left( \frac{z}{H_z} \right)^2 \right]; \quad i = 1, 2, \]  

\[ (5) \]
where $\rho$ is the polar radial distance from the Galactic center, $z$ is the distance from the Galactic plane, and $\dot{N}_1$ and $\dot{N}_2$ represent the central rate densities for the high- and low-luminosity sources.

We choose $L_2$ sufficiently small that the low-luminosity component is visible only to distances much less than the disk thickness, and thus appears to have a uniform density. An upper bound on $L_2$ is found by requiring that the low-luminosity bursters near the edge of the source ellipsoid produce events that are well below a peak flux of $\sim 1 \, \text{s}^{-1} \, \text{cm}^{-2}$. We take the rate at which photons are emitted in the BATSE trigger window (50-300 keV) for each source as $L_i/\epsilon$, where $\epsilon \approx 300 \, \text{keV}$. The implied limit on the power of the low-luminosity component is then

$$L_2 \ll 5 \times 10^{40} \left( \frac{H_z}{20 \, \text{kpc}} \right)^2 \, \text{erg s}^{-1},$$

(6)

where we have assumed spherically-symmetric emission. The fiducial normalization of equation (4) was chosen because, as we show below, acceptable models have values of $H_z$ as small as 20 kpc.

The rate at which bursts occur with a peak energy flux exceeding $P$ is

$$\dot{N}(P) = \int_0^\pi d\theta \sin \theta \int_0^{2\pi} d\phi \int_0^{d_1(P)} dr \, r^2 \, \dot{n}_1(\rho, z) + \frac{\dot{N}_2}{6\pi^{1/2}} \left( \frac{L_2}{\epsilon P} \right)^{3/2},$$

(7)

where $\phi$ is the angle of the source around the Galactic center measured from the Galactic plane, $r$ is the distance from the observer to the source, and $d_1(P) \equiv (L_1/4\pi\epsilon P)^{1/2}$ is the distance to a high-luminosity source with observed flux $P$. The distances $\rho$ and $z$ are related to $\theta$ and $\phi$ by

$$\rho^2 + z^2 = R_0^2 + r^2 - 2R_0 r \cos \theta; \quad z = r \sin \phi \sin \theta,$$

(8)

where $R_0 = 8.5 \, \text{kpc}$ is the assumed distance to the Galactic center.

The second term in Eq. (7) represents the homogeneous, isotropic contribution from the low-luminosity bursters. It gives $-3/2$ logarithmic slope, while the high-luminosity
bursters produce deviations from this behavior at low flux. In terms of these variables, the dipole moment for a sample of bursts with fluxes exceeding \( P \) is

\[
\langle \cos \theta \rangle_P = \frac{1}{N(P)} \int_0^\pi d\theta \sin \theta \cos \theta \int_0^{2\pi} d\phi \int_0^{d_1(P)} dr r^2 \hat{n}_1(\rho, z),
\]

(9)

and

\[
\langle \sin^2 b \rangle_P = \frac{1}{N(P)} \left( \int_0^\pi d\theta \sin^3 \theta \sin^2 \phi \int_0^{2\pi} d\phi \int_0^{d_1(P)} dr r^2 \hat{n}_1(\rho, z) + \frac{\hat{N}_2}{18\pi^{1/2}} \left[ \frac{L_2}{\epsilon P} \right]^{3/2} \right).
\]

(10)

For \( \hat{N}_2 \gg \hat{N}_1 \), the quadrupole moment \( [\langle \sin^2 b \rangle_P - 1/3] \) vanishes.

This model has five adjustable parameters: \( H_\rho, H_z, L_1, \hat{N}_1 \) and \( \hat{N}_2 L_2^{3/2} \). We have searched this five dimensional parameter space for models that are consistent with the observed angular and number-flux distributions. Our consistency criteria are:

- The \( \chi^2 \) difference between the model differential distribution \( (dN_P/d\ln P) \) and the observed distribution must be less than 1.5 per degree of freedom.

- The model’s dipole and quadrupole moments must not differ from the data by more than 1.5 standard deviations for any observed peak flux.

Figure 5 shows the region in the \( H_\rho-H_z \) plane where acceptable models are found. The acceptable models are thick disks with aspect ratios \( H_\rho/H_z \sim 1.5 \). The smallest allowed models, which we call compact models, have dimensions of \( H_\rho \sim 30 \text{ kpc} \) and \( H_z \sim 20 \text{ kpc} \). Figs. 1-4 show the agreement of a compact model with the angular and flux distributions.

\(^1\)For the two bins of lowest peak flux, the instrument efficiency corrections significantly affect the estimated number. Because these corrections are not well-determined, we take the half range between the highest corrected number and the lowest uncorrected number as the standard deviation, with the center of this range as the most likely value.
In these compact models the high-luminosity component has a peak luminosity of $L_1 \simeq 10^{42}$ erg s$^{-1}$ and a central rate-density factor of $\dot{N}_1 \sim 3 \times 10^{-4}$ yr$^{-1}$ kpc$^{-3}$. The low-luminosity component is characterized by $(\dot{N}_2/10^{-2}$ yr$^{-1}$kpc$^{-3})(L_2/10^{40}$ erg s$^{-1})^{3/2} \simeq 6$. Combining this relationship with the limit of Eq. (3) gives $\dot{N}_2 \gg 5 \times 10^{-3}$ yr$^{-1}$ kpc$^{-3} (H_z/20$kpc$)^{-3}$. This rate-density can be accommodated by a population of Galactic neutron stars that fill the thick disk and occasionally produce gamma-ray bursts. For example, if the thick disk contained $10^8$ neutron stars each of which produced a low-luminosity burst approximately every $t_{\text{rep}}$ years, the central rate-density would be $\dot{N}_2 \sim 350/t_{\text{rep}}$ yr$^{-1}$ kpc$^{-3} (H_z/20$kpc$)^{-3}$, if we assume the aspect ratio is $H_\rho/H_z = 1.5$. Consistency with the observed gamma-ray burst rate requires $t_{\text{rep}} \ll 7 \times 10^4$ yr, an acceptable bound for burst repetitions.

The dashed lines in Fig. 1 show the cumulative moments of the compact models; the offsets due to incomplete sky coverage ($\langle \cos \theta \rangle_{\text{iso}}, \langle \sin^2 b - 1/3 \rangle_{\text{iso}}$) have been added. The dotted lines in Fig. 2 give the statistical residuals between the data and the compact model results. The selection process for the acceptable models ensures that these residuals are smaller than those for the isotropic hypothesis. Figure 3 shows that the compact model yields a number-peak flux distribution that is consistent with the BATSE data. At the faint end, the model falls far below the corrected BATSE data point. However, because the BATSE detector efficiency is not accurately known for the lowest peak fluxes (Meegan, private communication), this discrepancy is not necessarily significant. Figure 4 shows that the observed and predicted cumulative distributions are also in good agreement, except for the poorly-determined faint end of the distribution.

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$^2$The normalization of the full sky burst rate was fixed to match the cumulative rate of 550 yr$^{-1}$ at $P = 1$ cm$^{-2}$ s$^{-1}$ determined from the 1B catalog (Fishman, et al. 1994).
4. SUMMARY AND CONCLUSIONS

The BATSE 3B catalog shows indications of a brightness-dependent anisotropy suggesting that the brighter sources cluster toward the Galactic plane, and to a lesser extent, the Galactic center. This clustering, if a reflection of the true GRB angular distribution, is inconsistent with the cosmological interpretation. We show that the observed angular and flux distributions are consistent with a Galactic distribution of bursters residing in a thick disk, with a bimodal luminosity function. Most bursts originate from low-luminosity, nearby sources while the relatively few ($\lesssim 5\%$) high-luminosity sources trace the shape of the thick disk. The high-luminosity sources have peak luminosities $\simeq 10^{42}$ ergs s$^{-1}$, and are at least 25 times more luminous than the low-luminosity sources. We find that the dimensions of the disk can be as small as 20 kpc in thickness and 30 kpc in radial extent; this GRB source distribution is more compact than normally considered viable (see, e.g., Briggs et al. 1996). If the Andromeda Galaxy contained a similar population of high-luminosity sources, their peak gamma-ray fluxes would be less than $\sim 0.1$ s$^{-1}$ cm$^{-2}$, making their detection problematic.

It would not be fruitful to attempt to use the data in the BATSE 3B catalog to determine whether this two-component thick disk model is preferred over the isotropic interpretation. Since our thick-disk model was motivated by the 3B data, we do not attribute statistical significance to the agreement between the model and the data. On the other hand, data taken since the compilation of the 3B catalog may be able to distinguish between these two interpretations. As Fig. 1 shows, the expectations of the thick-disk and the isotropic interpretations are quite different. Only one or two years may be sufficient to establish whether the trends of the two-component thick-disk models are borne out by the new data.
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Fig. 1.— The cumulative Galactic moments as functions of peak flux. The left panel shows the dipole moments and the right, the quadrupole moments. The solid lines show the observed values, and the horizontal lines are the expected values for an isotropic distribution of bursts. The dotted lines are expected values for a compact thick-disk model with $H_z = 20$ kpc and $H_\rho = 30$ kpc.

Fig. 2.— The statistical residuals of cumulative Galactic moments as functions of peak flux. The panels and lines are as in Fig. 1.

Fig. 3.— The differential number peak flux distribution, adapted from Meegan et al. (1996, Fig. 10a). Shown is the number of bursts per factor of 1.55 in peak flux, equivalent to $0.438 \frac{dN_p}{d\ln P}$. The upper error bars for the two lowest flux bins include corrections for detector efficiency. The curve represents a compact thick-disk model with $H_z = 20$ kpc and $H_\rho = 30$ kpc. The dash-dotted line shows the $-3/2$ power law expected for a homogeneous burst distribution.

Fig. 4.— The cumulative number distribution. The thin solid line is the observed distribution, and the thick solid curve is for a compact thick-disk model with $H_z = 20$ kpc and $H_\rho = 30$ kpc. The dotted line represents the contribution from low-luminosity sources, while the dashed line is for the high-luminosity sources.

Fig. 5.— The allowed region of the $H_\rho$-$H_z$ plane for two-component Galactic gamma-ray bursts.
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peak flux (cm$^{-2}$ s$^{-1}$)
peak flux (cm$^{-2}$ s$^{-1}$)
peak flux (cm$^{-2}$ s$^{-1}$)

number of bursts

peak flux (cm$^{-2}$ s$^{-1}$)
allowed