J. Astron. Space Sci. 19(1), 1–6 (2002)

ON SPATIAL DISTRIBUTION OF SHORT GAMMA-RAY BURSTS FROM EXTRAGALACTIC MAGNETAR FLARES

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(Received February 1, 2002; Accepted February 9, 2002)

ABSTRACT

Recently, one interesting possibility is proposed that a magnetar can be a progenitor of short and hard gamma-ray bursts (GRBs). If this is true, one may expect that the short and hard GRBs, at least some of GRBs in this class, are distributed in the Euclidean space and that the angular position of these GRBs is correlated with galaxy clusters. Even though it is reported that the correlation is statistically marginal, the observed value of $< V/V_{\rm max} >$ deviates from the Euclidean value. The latter fact is often used as evidence against a local extragalactic origin for short GRB class. We demonstrate that GRB sample of which the value of $< V/V_{\rm max} >$ deviates from the Euclidean value can be spatially confined within the low value of z. We select very short bursts ($T_{90} < 0.3$ sec) from the BATSE 4B catalog. The value of $< V/V_{\rm max} >$ of the short bursts is 0.4459. Considering a conic-beam and a cylindrical beam for the luminosity function, we deduce the corresponding spatial distribution of the GRB sources. We also calculate the fraction of bursts whose redshifts are larger than a certain redshift z', i.e. $f_{>z'}$. We find that GRBs may be distributed near to us, despite the non-Euclidean value of $< V/V_{\rm max} >$. A broad and uniform beam pattern seems compatible with the magnetar model in that the magnetar model requires a small $z_{\rm max}$.

Keywords: theory – gamma rays, bursts – methods, statistical

1. INTRODUCTION

Even though gamma-ray bursts (GRBs) are widely accepted to be produced when fast-moving, relativistic shells ejected from a central source in a relatively short period collide with slowly moving, yet relativistic shells that were ejected at an earlier time (Rees & Mészáros 1994, Kobayashi, Piran, & Sari 1997), the origin of the observed GRBs is still unclear. This is partly why much of the current theoretical research on GRBs is aimed at determining the nature and the origin of the central engine (Narayan, Paczyński, & Piran 1992, Woosley 1993, Paczyński 1998, MacFadyen & Woosley 1999). It seems believed that the progenitors of long GRBs are produced in the late stage of massive stars (e.g., MacFadyen & Woosley 1999) and that their spatial distribution may follow the star-formation rate (SFR) of massive stars (Blain & Natarajan 2000). However, all the arguments are related to only a long GRB class. It is not yet clear whether long and short GRBs are due to the same progenitor. If the short bursts are due to another origin, above conclusions are applicable only to the long GRBs.

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Duncan (2001) recently suggested that the short and hard gamma-ray bursts (GRBs) could be accounted for by "Magnetic Flares" from the magnetar, which is a young neutron star with a strong magnetic field (Duncan & Thompson 1992). If this is the case, positions of this GRB population should be correlated with those of nearby extragalaxies or galaxy clusters and these GRBs could be detected by BATSE out to $z \sim 0.1\psi_8^{-1}$, where $\psi_8 = \psi/8°$, ψ being the full opening angle of the beam. As a result of this, the $< V/V_{\rm max} >$ of this population is "naturally" expected to have the Euclidean value, that is, 0.5. Even though Cline et al. (1999) reported that the $< V/V_{\rm max} >= 0.52 \pm 0.1$ for the extremely short bursts ($T_{90} \leq 0.1$ sec), this conclusion is controversial in that the value of $< V/V_{\rm max} >$ is subject to the way of sampling GRBs. The deviation has been used to argue against the magnetar origin of short and hard GRBs.

In order to make any conclusions on any physical information concerning the spatial distribution function $n(z)$ or the luminosity function $\Phi(L)$, however, one has to be cautious about these two functions. Chang & Yi (2001) have discussed that a luminosity function $\Phi(L)$ can be obtained for (almost) any given space density $n(z)$ such that the theoretical $< V/V_{\rm max} >$ curve fits the observed luminosity distribution, and vice versa. It is because $< V/V_{\rm max} >$ is the convolution of $n(z)$ and $\Phi(L)$ in a sense. For instance, they have found that the maximum redshift, $z_{\rm max}$, decreases as a product of the Lorentz factor and the opening angle of a conic beam increases by studying the statistical properties of luminosity functions deduced by the conic beam (Mao & Yi 1994, Chang & Yi 2001).

In this paper, we demonstrate that the smaller value than the Euclidean value of $< V/V_{\rm max} >$ does not necessarily imply that the distribution of the sample is non-Euclidean. We show how beaming-induced luminosity functions affect the statistics of the observed GRBs in the BATSE 4B catalog (Paciesas et al. 1999) considering the uniform distribution. A number density motivated by the star formation rate is irrelevant since we are concerning space to the extent of small z. We assume a flat universe with no cosmological constant, and adopt the Hubble constant $H_{\rm o} = 50$km/sec/Mpc, to which the conclusion of this work is very insensitive since the distance scale of interests is not very large.

2. OBSERVATIONAL DATA AND MODELS

The BATSE experiment on the *Compton Gamma Ray Observatory* detected and identified GRBs in space for a decade. We adopt the GRBs in the BATSE 4B catalog (Paciesas et al. 1999) and calculate their $< V/V_{\rm max} >$ for selected GRBs, using fluxes in channels 2 and 3 ($50 - 300$ keV). The BATSE 4B catalog provides 1637 triggered GRBs detected from 1991 April through 1996 August. We use the bursts which are detected on the 1024 ms trigger time scale. We choose the bursts of which peak count rates are above 0.4 photons cm^{-2}s^{-1} in order to avoid the threshold effects (cf. Mao & Yi 1994). Of those bursts, we further select the GRBs whose ratio of maximum count number to minimum count number $C_{\rm max}/C_{\rm min}$ is greater than 1.0, which gives a sample of 775 bursts. We choose bursts with durations $T_{90} < 0.3$ sec, where T_{90} is the time it takes to accumulate from 5 % to 90 % of the total fluence of a burst summed over all the four channels, which leaves 38 bursts. Noting that short bursts are basically hard as noted earlier by Tavani (1998) we adopt all the short bursts instead of dividing them in terms of the hardness once again. The number of data may not be enough to draw a rigorous conclusion in $< V/V_{\rm max} >$ analysis. However, it is backed up by $f_{>z'}$ plot in this study. Eventually, as the number of observed short GRBs increases the conclusion as of this study can be tested.

We calculate two statistical quantities using the conic beaming-induced luminosity function. First, we calculate the $< V/V_{\rm max} >$ as a function of the number of bursts. To compute $< V/V_{\rm max} >$

we need to know two functions : the spatial distribution density function, $n(z)$, and the luminosity function, $\Phi(L)$. As explained above, we consider the constant spatial distribution density function in this study since we are concerning space to the extent of small z.

$$\left\langle \frac{V}{V_{\rm max}} \right\rangle \equiv \left\langle \left(\frac{F_{\rm min}}{F}\right)^{3/2} \right\rangle$$
$$= \int_0^{z_{\rm max}} \left(\frac{F_{\rm min}}{F}\right)^{3/2} \frac{n(z)}{1+z} 4\pi r^2(z) dr(z) \Big/ \int_0^{z_{\rm max}} \frac{n(z)}{1+z} 4\pi r^2(z) dr(z), \quad (1)$$

where $n(z)$ is the number of bursts per unit comoving volume and $z_{\rm max}$ is the maximum redshift at which the burst with $F = F_{\rm min}$ is detected, $F_{\rm min}$ being the minimum flux. In the equation above, supposed $\int_0^{z(f)} \frac{n(z)}{1+z} 4\pi r^2(z) dr(z)$ be $\mathcal{N}$, then

$$\mathcal{N} = \int_{L_1}^{L_2} \Phi(L) dL \int_0^{r(L)} 4\pi n(r) r^2 dr, \quad (2)$$

where $r(L)$ is the the luminosity distance.

Second, we calculate the fraction of GRBs. We define the fraction of bursts located at a redshift larger than z$'$ as

$$f_{>z'} = \frac{N(z^{'} < z < z_{max})}{N(0 < z < z_{max})}, \quad (3)$$

where

$$N(z^{'} < z < z_{max}) = \int_{z'}^{z_{max}} \frac{4\pi}{1+z} n(z) r^2(z) dr(z), \quad (4)$$

where $z_{\rm max}$ is the maximum accessible redshift defined by $V_{\rm max}$, and $n(z)$ is the spatial distribution function of GRBs, that is, the rate of GRBs per unit time per unit comoving cosmological volume.

And the beaming induced luminosity function is adopted in this study. It is widely believed that GRBs are beamed (Sari, Piran & Halpern 1999). In this case, the luminosity function is naturally introduced by the random distribution of the space orientation of the cone axis. In our beaming model, the ejecta is flowing outward relativistically in a cone with the geometrical opening angle $\Delta\theta$. The observed gamma-ray emission is produced at radius R from the central engine. According to Mao & Yi (1994), the probability that we observe the bright bursts rapidly increases as the opening angle increases, while relatively dim bursts are not as detectable as brighter ones. Therefore, when the opening angle large ($\Delta\theta \gg 1/\gamma$), the derived luminosity function becomes similar to that of the standard candle case, in which all bursts have the same maximum luminosity given by this luminosity function. When the opening angle is small ($\Delta\theta \ll 1/\gamma$), the luminosity function gives the same result as the cylindrical beaming case as expected. The bulk Lorentz factor γ_0 is set to be 100 (e.g. Piran 1999).

The ejected material can have a structure in the bulk Lorentz factor $\gamma(\theta)$ at this distance and the photon-emitting electrons' density at the surface of the cone can be varying, which is considered in this study. We assume the axisymmetry of the Lorentz factor profile around the cone axis, $\gamma = \gamma(\theta^{'})$, and hence the Lorentz factor profile could mimic a simplified model for the jet-environment drag. At the center of the cone, γ has the maximum value and decreases with θ'. The window function adopted is the Gaussian, $\exp[-A(\frac{\theta^{'}}{\Delta\theta})^2]$ such that at the center of the cone γ has an original constant value, γ_0 (see Chang & Yi 2001).

We assume that the spectra of bursts are power laws in photon numbers, $n(\nu)d\nu \propto \nu^{-\alpha}d\nu$. The peak flux and peak count rate are simply determined by the peak intensity in the comoving frame. Note that the intensity $I_0(\nu_0)$ is related to the photon number spectrum by $I_0(\nu_0) \propto \nu_0 n(\nu_0) \propto \nu_0^{1-\alpha}$ and that the frequency is increased by a factor of $1+z$ due to the cosmological redshift. In order to compare with the observations, we have to calculate the peak count rate in a given band.

3. RESULTS

We plot the results obtained for the beaming-induced luminosity functions with the uniform distribution of burst sources in Figure 1. In the left panels, we plot the $< V/V_{\rm max} >$ curve as a function of number of bursts. Dotted lines represent the observed $< V/V_{\rm max} >$ with $\pm 3\sigma$ bounds, that is, the dotted line in the middle stands for the observational data and the upper and lower dotted lines $\pm 3\sigma$ bounds.

The short-dashed lines represent theoretical curves due to the luminosity function of the conic beam with the opening angle $\Delta\theta = 1^\circ.0$, the long-dashed lines due to the conic beam with the opening angle $\Delta\theta = 0^\circ.1$, the dot-dashed lines due to the cylindrical beam, that is, $\Delta\theta = 0^\circ.0$, the continuous lines due to the non-uniform conic beam with the opening angle $\Delta\theta = 1^\circ.0$ and $A = 4$. In the right panels, we show the fraction of GRBs. Different line types represent same meanings as in the left panels. Note that theoretical curves in the left panels are almost identical regardless of different input parameters.

According to the plots in the left panels, regardless of the photon index α all the luminosity functions seems to satisfy the observed $< V/V_{\rm max} >$ curve as long as the constant $n(z)$. It is, however, evident in the plots in the right panels that the maximum redshift becomes larger as the beaming angle becomes smaller. In particular, an angle-dependent gamma, $\gamma(\theta)$, is considered, the maximum redshift gets bigger. The maximum redshift becomes larger and larger as A increases.

It is interesting to note that, if we assume $\alpha = 1.0$, a large fraction ($\sim 60\%$) of short GRBs are distributed at higher redshifts $z \geq 1$, in the structured beaming model case that we have considered. However, even in this case when $\alpha = 2.0$, $z_{\rm max}$ is significantly reduced. Indeed, for $\alpha = 2.0$ case, short GRBs are distributed in Euclidean space. In other words, though their $\langle V/V_{\rm max}\rangle$ value is a non-Euclidean value, most of the short bursts can be distributed at low redshifts in the case of $\alpha = 2.0$.

4. DISCUSSIONS AND CONCLUSION

It is shown by Kouveliotou et al. (1993) that the GRB population is bimodal in their duration. There have been further attempts to divide the observed GRBs into more than two classes (Hakkila et al. 2000, Balastegui, Ruiz-Lapuente, & Canal 2001). It is natural to consider different progenitors for separate classes of the observed GRBs. There is no compelling reason to expect that separate classes of GRBs have a same progenitor model. Short GRBs may have different progenitors from those of long GRBs. Primodial black holes and magnetars are suggested as a possible progenitor of short GRBs (Cline & Hong 1992, Duncan 2001). If this is the case, these events are expected to be correlated in position with near galaxies (< 20 Mpc) and exist in near to us. Though several studies have claimed correlations of GRB positions with galaxy clusters at a statistically marginal level (e.g., Kolatt & Piran 1996), the observed value of non- Euclidean $< V/V_{\rm max} >$ is often used as evidence against a local extragalactic origin for short GRB class.

From this simple analysis we have carried out, we have shown that the beaming-induced lumi-

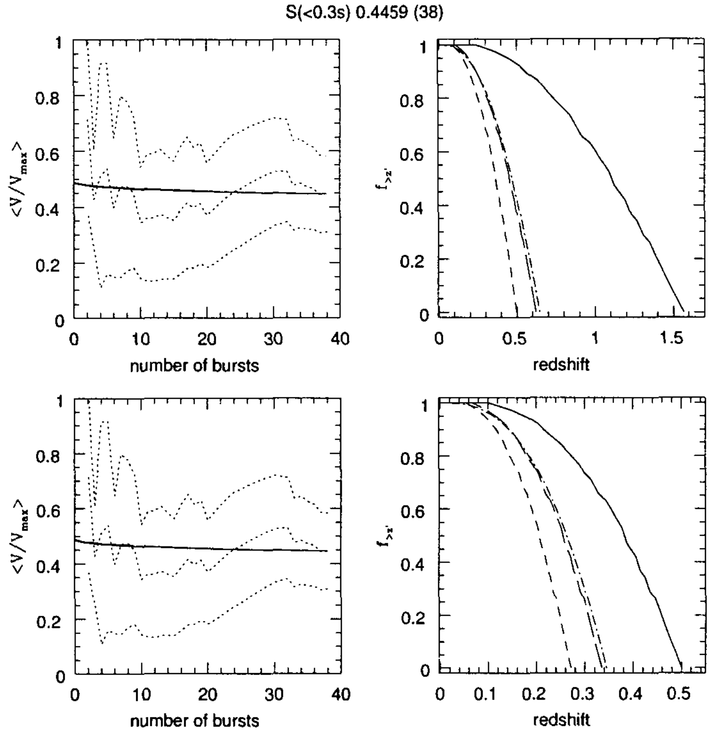

Figure 1. The $< V/V_{\max} >$ and $f_{>z'}$ are shown in left panels and right panels, respectively. The photon index α is assumed to be 1.0 and 2.0 in upper and lower panels, respectively. Note that the $z_{\max}$ becomes significantly smaller when $\alpha = 2.0$. Plots are generated with the data sample for $T_{90} < 0.3$ sec. The value of $< V/V_{\max} >$ resulting from the sample is 0.4459. The number in parenthesis on the top is the number of the data. For different line types result from different beaming-induced luminosity functions. See the text for details.

nosity function, which may be derived from a magnetar model, may account for the basic statistical properties of the observed Euclidean GRBs whose T_{90} is less than 0.3 sec. According to Figure 1, the deviation of the $< V/V_{\max} >$ from the Euclidean value can be reconciled by the beaming-induced luminosity function.

If the magnetar is indeed a progenitor of short and hard GRBs, the beaming pattern from the magnetar model is likely to be broad and smooth at the emission surface rather than narrow and hollow. Since the luminosity function of a broad beam is essentially that of the standard candle case, GRBs whose origin is the magnetar can be considered such that their luminosity function is same as that of the standard candle.

The photon index α is diverse in the sense that the spectrum parameters vary from burst to burst with no universal values. And studies on the spectral parameters are mainly done with the bright and long bursts than $T_{90} > 1$ sec, at least. So direct information on the short bursts is not available. However, provided that the photon index of short bursts is more or less similar to that of long bursts, the average of α for all bursts is reported as $1.8 - 2$ (Piran 1999).

One may attempt to further develop this study. In fact, for instance, it is not very clear and definite what we mean by the 'opening angle' $\Delta\theta$. It is generally thought that the curvature of the photon-emitting surface is $1/R_1$, where R_1 is the distance of the surface from the central engine. It is, however, not necessarily true that the curvature of the 'true' photon-emitting surface is same with $1/R_1$. Suppose that the curvature of the 'true' photon-emitting surface is given by $1/R_2$, where $R_1 \neq R_2$. The actual opening angle we should take is then given by $\Delta\theta_2 = \sin^{-1}[(R_1/R_2)\sin\Delta\theta_1]$, or for small $\Delta\theta_1$, $\Delta\theta_2 = [(R_1/R_2)\Delta\theta_1]$. In other words, in the calculations the definition of the opening angle of the uniform conic beam is rather $\Delta\theta_2$. In the current study of the magnetar model, the opening angle is given by $\Delta\theta_1$ which corresponds to the case that its curvature is R_1. So, if the curvature of the photon-emitting surface can be defined in a different way from $1/R_1$, our result cannot be used directly to imply anything about the physical magnetar model, unless we can say something about the curvature. In two extreme cases where $R_1/R_2 \gg 1, R_1/R_2 \ll 1$, the luminosity functions should look like those for the standard candle and for the cylindrical beaming, respectively.

ACKNOWLEDGMENTS: We are very grateful to Insu Yi and Robert Duncan for useful discussions and to Chunglee Kim for help in data analysis. We thank referees for useful comments which improve our presentation. One of us (H.I.K.) is supported in part by Korea Research Foundation under Grant KRF-2000-015-DP0080, and is grateful to Chang-Hwan Lee and to Sang-Hyeon Ahn for hospitality while visiting KIAS.

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