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Gamma-Ray Bursts and their Power Spectrum

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Abstract: Gamma ray bursts (GRBs) are known to have short-time variability and power-law behavior with the index -1.67 in the power spectrum density(PSD). Reanalyzing the expanded data, we have found a) the power-law in the PSD comes from the outline of the burst profile rather than fluctuations in short time scale. b) Although the power indices of the average PSD distribute around the value -1.67 with relatively small dispersion, the indices of individual PSD vary from burst to burst with large dispersion: the value -1.67 is given simply by averaging PSD whose indices are widespread.

1. Introduction

Gamma-ray bursts (GRBs) are one of the most energetic phenomena in the universe. There have been more than 2000 observation of GRBs since their first discovery in 1960s. Then, what are the GRBs? They are strong gamma-ray emission at cosmological distance. They last several milliseconds to several thousand seconds and their event rate is 10^{-6} per year per galaxy; in a galaxy once per million years. GRBs release $10^{51} \sim 10^{52}$ ergs in one event. Their angular distribution on the sky is isotropic.

However, the origin and the fundamental mechanism of the GRBs have not been revealed despite the fact that more than thirty years have passed since the first discovery of them.

There have been many works studying the luminosity profile itself of GRBs (for example, Norris et al. 1996; Stern 1996). We notice that most GRBs have very rapid milli-second time variability (Schaefer & Walker 1999; Walker, Schaefer, & Fenimore 2000) though there is vast variety in luminosity profile itself for each GRB.

We believe that this characteristic variability must have important information to reveal the GRB mechanism. Therefore, in this letter, we would like to concentrate on the analysis of this variability.

In studying time sequence of objects, the Fourier transform technique is useful and often yields indispensable information on the scaling properties and characteristic time scale. For example, Beloborodov, Stern, & Svensson (1998) used this method for 214 light curves of long GRBs ($T_{90} > 20\,\mathrm{sec}$) and reported that the averaged power spectrum density (PSD) of GRBs shows the power-law with the index 1.67 ± 0.02 over two decades in frequency range. This value is very closed to $-5/3$ which suggests the Kolmogorov spectrum of velocity fluctuations in turbulent medium.

On the other hand, the power-law in PSD does not necessarily specify the whole mechanism as we know in various examples. Actually the power-law in PSD can be derived by many reasons; some specific burst profile, Levy-type random noise[1] in the background, and the superposition of similar shots and so on. In fact, fluctuation in a luminosity profile realize the power-law behavior in the PSD, when the fluctuation is Levy-type random noise. The power-law in PSD of X-ray emission from stellar black hole candidates or Active Galactic Nuclei (AGN) are considered to be originated from the superposition of many similar shots (for example, Negoro et al. 1995; Mineshige & Yonehara 2001).

Here in this paper, we would like to determine the origin of the power-law in PSD of GRBs by analyzing the detail of PSD for each burst data.

First, we demonstrate that the individual PSD of GRBs does not exactly have the power-law index -1.67 but has wide variation. Second, we argue that power-law index of PSD is determined by the profiles of an individual shot in the light curve and not by the superposition of many similar shots nor by Levy-type random noise. Then we discuss the general nature of PSD of superposed shots and apply this method to the actual data of GRB light curves. Finally we observe how the averaged PSD shows clear power-law index -1.67.

2. Power Law in PSD of GRB

In our analysis, we use the data detected by the Burst and Transient Source Experiment (BATSE) on Compton Gamma Ray Observatory (CGRO) with 64ms resolution[2]. We use the light curves in the energy band $20 < h\nu < 50$ keV, $50 < h\nu < 100$ keV,$100 < h\nu < 300$ keV,$30 < h\nu$ keV. For excluding the noise contamination, we select the data with peak count rate larger than 250 counts per 64ms bin; finally 297 data set remain.

[1] Peak intensity distribution of this type noise follows power law.
[2] ftp://cossc.gsfc.nasa.gov/pub/data/batse/ascii_data/64ms/

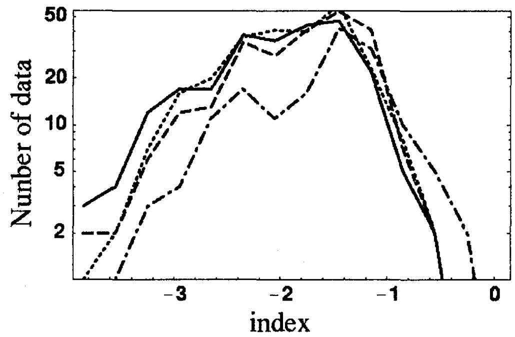

Figure 1: The distribution of the power index α. We excluded the data which could not fit well with the function of equation(1). Each line corresponds the energy band $20 < h\nu < 50$ keV (solid line), $50 < h\nu < 100$ keV (dotted line),$100 < h\nu < 300$ keV (dashed line), $30 < h\nu$ keV(chain line).

In order to see the generality of the power index $-5/3$, we first calculate the power spectra, which is the absolute square of the Fourier transform of the time sequence, for individual light curves. We assume the following fitting function for the power spectrum $P(f)$, expecting the coexistence of the power-law component and the thermal white-noise component.

$$P(f) = Af^{\alpha} + B. \tag{1}$$

Figure 1 shows the distribution of power-law index α thus obtained.

We emphasize here that the power index is widely distributed. We checked the bin-size (of indices) dependence of our result: The dependence is negligibly small within the bin-size from 0.1 to 0.4.

3. What Determines The Individual Power Law?

Now let us consider the meaning of the power-law in PSD. As is well known, the power-law itself in the PSD can be realized in various origin. The specifications of the origin is significant for the analysis of the central engine of GRBs.

At least the following three ways can realize the power-law in PSD.

1. Outline of the burst profile.
2. Levy-type random process.
3. Superposition of self-similar shots.

We examine the above possibilities in the following in this order.

First, we examined the first possibility. We realize that each GRB data generally has multiple shots and rapid fluctuations as well as noise whose origin is not seem to be GRB. We try to identify these components in each GRB data step by step.

First we discuss the light curve with a single shot. This simple type of light curve shows a clear power-law behavior in its PSD. We consider the following two model cases; a) the decay type, and b) the grow-and-decay type.

The decay type shot has the flux x at time t as

$$x(t) = ht^{-p}\exp(-f_0 t)\theta(t), \tag{2}$$

where the positive parameters h, p and f_0 respectively represent "intensity", "sharpness" and "inverse of the duration" of the shot. $\theta(t)$ is the step function. Power spectrum P for this shot is written as

$$P(f) = h^2[\Gamma(1-p)]^2\left[f_0^2 + f^2\right]^{p-1}, \tag{3}$$

where $\Gamma(x)$ is the Gamma function.

The grow-and-decay type shot generally has asymmetric profile in the burst; we separate the grow (left side) and decay (right side) of the shot. Each side of the shot is written as

$$\begin{aligned} x(t) &= h_L(-t)^{-p_L}\exp(tf_{0L})\theta(-t) \\ &\quad + h_R(t)^{-p_R}\exp(-tf_{0R})\theta(t). \end{aligned} \tag{4}$$

Power spectrum of this type is written as

$$P(f) = h_L^2\{\Gamma(1-p_L)\}^2\left(f_{0L}^2 + f^2\right)^{p_L - 1}$$

$$+ h_R^2\{\Gamma(1-p_R)\}^2 \left(f_{0R}^2+f^2\right)^{p_R-1}$$
$$+ 2h_L h_R \Gamma(1-p_L)\Gamma(1-p_R)$$
$$\times \left(f_{0L}^2+f^2\right)^{\frac{p_L-1}{2}} \left(f_{0R}^2+f^2\right)^{\frac{p_R-1}{2}}$$
$$\times \cos\left[(p_L-1)\theta_L+(p_R-1)\theta_R\right], \tag{5}$$

where $\theta_{\rm L,R} = \arctan\left(f/f_{0\rm L,R}\right)$.

Since the GRB data generally has multiple shots, the above single shot profiles must be superposed before we use. For simplicity for fitting procedure, we assume that all shots in the individual light curve has the same profile except the overall amplitude [3]; i.e. the k-th shot in the light curve $x_k(t)$ is written as $A_k x(t-a_k)$, where A_k is the relative amplitude and a_k is the location of the k-th shot with $x(t)$ being the fixed function for each GRB data. Then we can easily calculate the PSD for multiple shots since the Fourier transforms of the first and the k-th shots are simply related with each other as $\tilde{x}_k = A_k e^{ifa_k}\tilde{x}_1$.

The light curve $x_T(t)$ which has n shots

$$x_T(t) = \sum_{k=1}^{n} x_k(t), \tag{6}$$

has the PSD

$$P_T(f) = P(f)\left[\sum_{j=1}^{n} A_j^2 + \sum_{j>k} 2A_jA_k\cos f(a_j-a_k)\right], \tag{7}$$

where $P(f)$ is PSD for $x(t)$.

It is apparent that the last expression consists of the "constant" term and the "oscillating" term; the former term determines the rough profile of PSD and the latter fluctuations around it.

We can actually see this structure in PSD of GRB data. We first identify the maximum shot in the GRB data and locally fit this shot by the single-shot form argued in the above (free parameters are p, f_0 and h). Then we subtract this first fit from the original data yielding one-shot subtracted data. Second, we identify the maximum shot in this subtracted data and locally fit this shot by the single-shot form with the same parameter p (the free parameters are f_0 and h). Then we subtract this second fit from the one-shot subtracted data yielding two-shots subtracted data. After repeating this process several times, the reduced data becomes almost flat.

We applied this method for many individual GRB data. One typical example for GRB910602(BATSE trigger number 257) is shown in Fig.2. Here we use the decay type shot for fitting identifying two shots in the data. The full PSD of this light curve is plotted in Fig.3 with the solid line. The PSD of the superposition of the first and the second fits is plotted with the dashed line. It is almost clear that the PSD of the superposition of first few fits are sufficient to faithfully reproduce the main part of the original PSD.

In high frequency the PSD of superposition of fits different from original PSD. In this frequency region, original PSD does not follow the power law. We interpret that as the influence of noise.

Other GRB data sets show similar behavior as this one.

Thus we have confirmed the first possibility: Outline of the burst profile determines the power-law behavior in PSD.

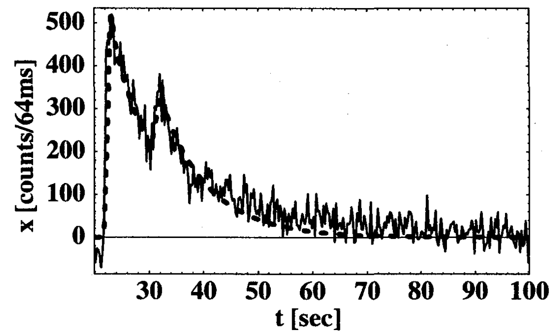

Figure 2: Actual light curve GRB910602(#257) (solid line) and fitting shots (dashed line); the superposition of the first and the second fits. The parameter p is 0.03.

[3] When we fit actual data of GRBs, we use inverse of duration f_0 as a fitting parameter, but it does not change the index of PSD at all.

In order to exclude the second possibility, the Levy-type random process, we have examined the peak distribution analysis. We calculate the distribution function of all peak-intensity in the data of artificially produced Levy-type light curve and that in the actual data of GRBs. The former shows a clear power law however the latter does not. We can now claim that the power-law in PSD of GRBs is not originated from the Levy-type random process.

In order to exclude the third possibility i.e. superposition of self-similar shots, we calculate the PSD of the few-shots subtracted data. For the previous data set, we calculate the PSD of the two-shots subtracted data in Fig.3 with the dotted line. This residual component is 10-100 times smaller than the main component and is almost flat. If GRBs have self-similar structure in their light curves, the few-shots subtracted data should also show power law (but its range might be narrower than that of original data). Thus we can now claim that the power-law in PSD of GRBs is not originated from the superposition of self-similar shots.

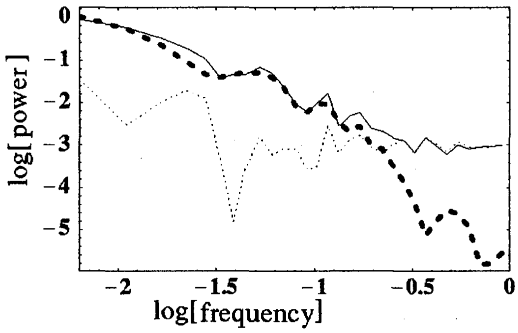

Figure 3: PSD of the light curve in Fig.2. We plot PSD of actual data (solid line), PSD of the superposition of the first and the second fits (dashed line) and PSD of the two-shots subtracted data (dotted line). PSD of the original data is hierarchically decomposed into the first shot, second shot and the small fraction of the subtracted component; our method is successfully working. Power index of this data is -1.95.

4. What Determines The Averaged Power Law?

We have averaged all the 297 PSD of GRB data. Figure 4 show the fit of this averaged PSD (solid line). Before taking the average, we have normalized each GRB luminosity data so that the maximum of the count rate be unity. This is because the original light curves have two to three orders of difference in maximum count rates and therefore the naively averaged PSD is determined by few GRB data. We have also tried the total-count-rate (fluence) normalization as well as maximum-count-rate normalization; yielding little difference between them as compared with the dispersion of individual indices.

Thus averaged PSD shows much clear power-law (Fig.4) than the individual PSD of GRB data. From Fig.4 we again observe that the individual PSD shows power-law and the power index simply fluctuates variously. After the superposition of many PSD data, there appears smooth power-law behavior with the power index of the central value. It is important to observe in Fig. 4 that there is no systematic correlation in each PSD to yield the global smooth power-law behavior. Especially there is no systematic distribution of time scales nor correlation of turning points which, if any, would have yielded clear envelope when many PSD are superposed.

If the clear power-law were realized by the envelope of many systematic distribution of burst time scales, the averaged power index would be significantly smaller than the mean power index.

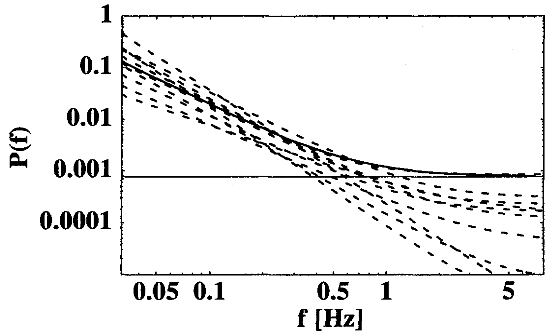

Figure 4: Fits of individual (dotted lines) and average (solid line) power spectra. We plot oldest 10 data of individual power spectra out of 297, and plot average of all 297 data.

5. Conclusions and Discussions

Analyzing 297 power spectrum density (PSD) of GRBs, we obtain the following results in this paper. a) Individual GRB data shows power law behavior in the PSD. The power index (α) is widely distributed. b) Power law behavior in PSD for individual GRB data is determined by the shot profile and not by the Levy-type noise nor the superposition of many self-similar shots. c) Power law index in averaged PSD is simply determined by the mean value of the index (α) distribution. We found no correlation mechanism for producing clear power law in averaged PSD.

The result b) conflicts with the interpretation that the turbulence (Beloborodov et al. 1998; Beloborodov, Stern, & Sevensson 2000) is the origin of the power law in PSD of GRBs. This is because the self-similar cascade of eddy, which would naturally yield many self-similar shots in the emission, necessarily yields the Kolmogorov power-law spectrum of velocity fluctuations in turbulent medium.

As Chang & Yi (2000) suggested, the problem of whether the bin size of luminosity profile is short enough or not remains. Moreover, we adopt the fitting function $Af^{\alpha} + B$ which contain the noise level in its form to avoid the influence of noise, but this function still not perfectly avoid the influence of noise. We should note that the value of index itself is not enough to decide the nature of emitting region of GRBs.

As we have seen in our analysis, some special form of shots, which yield the power law in PSD, is very characteristic and would be a good criterion for restricting various models of GRB generation mechanisms. The special shot profile is more severe checking point of the validity of the model than simply the power-law behavior of PSD (Panaitescu, Spada, & Mészáros 1999; Spada, Panaitescu, & Mészáros 2000). An urgent interest then would be the question whether the popular "Internal shock model" can explain these special shot profiles.

There are still important questions to be answered in the near future. 1) The shots in the light curves of GRBs have distinctly different two types; the decay type and the grow-and-decay type. This property is different from that of blazars, even if their similarity in emission process is often suggested. 2) What is the distribution of the sharpness parameter p and the ratio of power-law component and noise A/B in equation (1) ?

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