The Power Spectra of Two Classes of Long-duration Gamma-ray Bursts

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Abstract

We have studied the averaged power density spectra (PDSs) of two classes of long-duration gamma-ray bursts in the recent classification by Balastegui et al.(2001) based on neural network analysis. Both PDSs follow a power law over a wide frequency range with approximately the same slope, which indicates that a process with a self-similar temporal property may underlie the emission mechanisms of both. The two classes of bursts are divided into groups according to their brightness and spectral hardness respectively and each group’s PDS was calculated; For both classes, the PDS is found to flatten both with increasing burst brightness and with increasing hardness.

Key words:  Gamma rays: bursts—Gamma rays: theory

1. INTRODUCTION

Gamma-Ray Bursts (GRB) are transient and violent phenomena in which an energy of $\sim 10^{51} - 10^{53}$ ergs is released in a few seconds, in the form of $\gamma$ rays. They were first discovered by the USA Vela satellite in 1967, but we still know very little about their nature. The BATSE (Burst and Transient Source Experiments) on board the Compton Gamma-Ray Observatory (CGRO) of USA launched in 1991, has since observed over 2000 GRBs. These bursts show a great diversity as regards duration, peak flux and form of the energy spectrum, as well as time profile. This indicates that the process of GRB generation may be very complex. Meanwhile, the time profiles are richly packed with information on the GRB mechanism, and the study of their temporal properties is a valuable path to their understanding.

Beloborodov et al.(1998, 2000) calculated the average Fourier power density spectrum (PDS) of some bright and long gamma-ray bursts. They found the average PDS follow a power law over almost 2 decades of Fourier frequencies with two deviations (breaks), one at the low frequency end and one at the high frequency end. The low frequency break is caused by the finite durations of the bursts, i.e., the “window effect”; the high frequency break at 1~2 Hz can be related to a typical time scale of 0.5~1 s. Variabilities taking place on time scales shorter than that either do not exist, or are suppressed by
some mechanism. Power-law fitting to the average PDS gives an index of -5/3, the same slope of the Kolmogorov spectrum describing velocity fluctuations in a turbulent medium. These results suggest the presence of a physical process which is self-similar over a wide range of time scales, possibly turbulence in magnetic field (Stern, 1999).

A number of models have been proposed to explain the “central engine” of GRBs, merger of two neutron stars, of a neutron star and a black hole, collapse of a massive star, rapidly spinning and strongly magnetized compact objects, phase transition of compact objects, accretion onto massive black holes, and so on (Cheng & Lu, 2001). Do all GRBs have the same origin and mechanism? Or can they be divided into different classes according to origin? This is an attractive problem.

The best known classification is the classification into a short-duration class ($T_{90} < 2 \text{ s}$) and a long-duration class ($T_{90} > 2 \text{ s}$), $T_{90}$ being the interval between the times of 5% and 95% cumulative photon counts. The short bursts have harder energy spectra, and the long bursts, softer ones (as represented by the hardness ratio $H_{32}$) (Kouveliotou et al., 1993). Some people tried a multivariate classification with the duration, hardness, brightness, etc., as variates (e.g., Mukherjee et al., 1998, Balastegui et al., 2001). Balastegui et al. (2001) applied neural network analysis and divided 1599 bursts into 3 classes: Class I (531 bursts) corresponds to the “short” class of the above classic classification, and Class II (341) and class III (727) together correspond to the “long” class. See Fig. 1. The authors suggest that the two new classes of long bursts may correspond to different progenitors: Class II to mergers of two neutron stars, or a neutron star and a black hole; Class III to collapse of massive stars.

In this paper, we try to analyze the results of Balastegui’s classification as regards their average PDS. Different from the bulk quantities of GRBs, the PDS can depict temporal properties of the whole light curve, and may reflect information that is directly related
to the physical process of their generation. Therefore, a PDS investigation can serve as an independent test of the reclassification. Now, most of Class I have too short duration for the Fourier PDS calculation; moreover, many lines of evidence point to the $T_{90} < 2$ s bursts belonging to a different class of objects (Qin et al., 2000; Hakkila et al., 2000). So only bursts of Class II and Class III are included in our investigation.

2. CALCULATION OF AVERAGE PDS

For every individual burst, we use concatenated 64ms data summed over energy channel 2 (50~100 KeV) and channel 3 (100~300 KeV), recorded by the LAD detectors of BATSE. The average PDS is calculated according to the following procedure:

1. Select bright and long bursts. For dim bursts, the low signal to noise ratios will reduce the reliability of calculated results; and for bursts of too short durations, the “window effect” will severely distort the shape of the PDS. From Balastegui et al. (2001)’s sample, we therefore selected bursts with $T_{90} > 10$ s and with $P_{1024} > 0.4$ photons cm$^{-2}$ s$^{-1}$ ($P_{1024}$ is the peak flux recorded with 1024 ms time resolution, and is taken as a measure of the brightness).

2. Calculate the PDS of individual burst. First, the background is subtracted from the light curve. We then calculate the Fourier transform of each light curve, using the standard Fast Fourier Transform method. The power density at frequency $f$ is the squared amplitude of the Fourier transform at $f$. The power density of Poisson noise is equal to the total photon count of the light curve including the background. We calculate the individual Poisson noise power density and subtract it from the burst PDS.

3. Averaging of PDS. Normalization of the individual PDS is needed before the averaging. We use the peak-normalization procedure: we determine the peak count rate, $C_{peak}$ [photons per 64 ms], with the background subtracted, and normalize the individual PDS by $C_{peak}^2$. The average PDS is then calculated by summing up the normalized PDSs and dividing by the number of bursts.

3. RESULTS AND ANALYSIS

The resulting average PDSs of the two classes of bursts are plotted in Fig. 2. Both show a power-law form, $P_f \propto f^\alpha$, over a frequency range of more than one decade. There are deviations (breaks) from the power-law at the low frequency end and the high frequency end. The high frequency end break for the Class II bursts is not well determined because of the small sample size. The locations of the low frequency break for the two classes are different, because they have different average burst durations. In the case of peak-normalization, a burst with a longer duration have a greater fluence, and consequently gives a larger Fourier power. Since the Class III objects have, on average, longer durations, their PDS curve consequently lies above that of the Class II objects, as is shown in Fig. 2.

We fitted the average PDSs of the two classes with the power law $P_f \propto f^\alpha$ using the $\chi^2$ fitting procedure. The fitting results are listed in Table 1; also listed are the average
values of the duration $T_{90}$, peak flux $P_{1024}$ and hardness ratio $H_{32}$ (defined as the fluence ratio of channel 3 to channel 2). The fact that the power-law index $\alpha$ of the average PDS decreases with the average burst brightness was found by Beloborodov et al. (2000), and this finding is confirmed by our results (see below). Because our sample includes a greater number of dimmer bursts, the power-law index of our average PDS is less than $-5/3$.

Table 1: The average PDSs for class II and class III from neural network analysis.

<table>
<thead>
<tr>
<th>Class</th>
<th>Number</th>
<th>$T_{90}$/s</th>
<th>$P_{1024}$/ph cm$^{-2}$s$^{-1}$</th>
<th>$H_{32}$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>206</td>
<td>28.9</td>
<td>0.92</td>
<td>3.03</td>
<td>-1.84</td>
</tr>
<tr>
<td>III</td>
<td>650</td>
<td>74.3</td>
<td>4.28</td>
<td>3.15</td>
<td>-1.78</td>
</tr>
</tbody>
</table>

We divided the bursts of the two classes into groups of approximately the same size, according to their peak fluxes ($P_{1024}$) and to their hardness ratios ($H_{32}$), respectively. For each group we calculated its average PDS, which in every case showed a power law form. Their power-law indices $\alpha$, are plotted against $P_{1024}$ and $H_{32}$, in the two panels of Fig. 3. We see that, for both Class II and Class III objects, the average PDS flattens both with increasing peak brightness and with increasing hardness ratio.

Flattening of the average PDS implies an increase of the components of short time-scale variabilities. Now, GRBs are usually supposed to be at cosmological distances; dimmer bursts are more distant. Given that different (brightness) groups of bursts are
at different cosmological distances, the question arises, could the decrease in $\alpha$ be caused by cosmological time dilation? But time dilation stretches the entire light curve: for any given spectral structure its Fourier frequency is lowered by a factor independent of that frequency. Therefore, if the PDS is a power-law, time dilation will not change its slope. We therefore conclude that the increasing short time-scale variabilities, as indicated by the flattening average PDS, reflects an evolution of temporal properties of some intrinsic dynamic process of the GRBs.

4. DISCUSSION

As shown by our calculation, the two classes of long GRBs, in the new classification of Balastegui et al. (2001), do not show any notable difference as regards the shape and structure of their average PDSs, except for some trivial differences between their fitted power-law indices. The power-law form of the average PDS indicates that a physical process which has self-similarity over a wide time-scale range may be at work in both two classes. This process was supposed by some to be turbulence in magnetic field (Stern, 1999). Many different models of the progenitors of GRBs can give rise to the required “fire ball”; Balastegui et al. (2001) even claimed that the three classes of GRBs in their classification correspond to three kinds of progenitors. But our results about the average PDSs of the two long GRB classes calculated directly from the GRB light curves indicate that the light curves are not sensitive to the progenitors, even if the two classes originate in different progenitors. It is probable that both classes undergo a phase of relativistic expanding “fire ball”, in which energy is dissipated via magnetic reconnection explosion caused by turbulence (Stern, 1999). After the “fire ball” phase, information about the progenitor is lost. On the other hand, if GRB light curves are supposed to contain information about the progenitor, since some theoretical models of GRBs do not essentially need the “fire ball” phase, then our results reduces the probability that these long bursts have different origins.
Beloborodov et al. (2000) and Pozanenko et al. (2000) found that the average PDS flattens with increasing burst brightness. Under the assumption of cosmological origin and a “standard candle”, i.e., brighter bursts have smaller redshifts, and also assuming all bursts have the same mechanism, we saw that the redshift will not alter the shape of the average PDS (section 3). We conclude that the trend of the average PDS flattening with increasing brightness indicates that there exists an evolution of sources, at least an evolution in the temporal properties of the generation processes of GRBs.

The other trend of the average PDS flattening with increasing hardness ratios may be associated with another observational fact — the pulses in the GRB’s light curve are narrower in higher energy channel (the pulse is a fundamental morphological entity of the GRB light curve) (Norris et al., 1996). Furthermore, Beloborodov et al. (2000) showed that the average PDS gets flatter from energy channel 1 to channel 4. The trend we obtained that the average PDS flattens with hardness ratios is consistent with their result.

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References