POWER DENSITY SPECTRA OF GAMMA-RAY BURSTS
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ABSTRACT

Power density spectra (PDSs) of long gamma-ray bursts (GRBs) provide useful information on GRBs, indicating their self-similar temporal structure. The best power-law PDSs are displayed by the longest bursts (T90 > 10 s) in which the range of self-similar timescales covers more than 2 decades. Shorter bursts have apparent PDS slopes more strongly affected by statistical fluctuations. The underlying power law can then be reproduced with high accuracy by averaging the PDSs for a large sample of bursts. This power law has a slope $\alpha \approx -5/3$ and a sharp break at $\sim 1$ Hz. The power-law PDS provides a new sensitive tool for studies of GRBs. In particular, we calculate the PDSs of bright bursts in separate energy channels. The PDS flattens in the hard channel ($hv > 300$ keV) and steepens in the soft channel ($hv < 50$ keV), while the PDS of bolometric light curves approximately follows the $-5/3$ law. We then study dim bursts and compare them to the bright ones. We find a strong correlation between the burst brightness and the PDS slope. This correlation shows that the bursts are far from being standard candles and dim bursts should be intrinsically weak. The time dilation of dim bursts is probably related to physical processes occurring in the burst rather than to a cosmological redshift.

Subject heading: gamma rays: bursts

1. INTRODUCTION

The light curves of gamma-ray bursts (GRBs) typically have many random peaks, and in spite of extensive statistical studies (e.g., Nemiroff et al. 1994; Norris et al. 1996; Stern 1996) the temporal behavior of GRBs remains a puzzle. Contrary to the complicated diverse behavior in the time domain, long GRBs show a simple behavior in the Fourier domain (Beloborodov, Stern, & Svensson 1998). Their PDS is a power law of index $\alpha \approx -5/3$ (with a break at $\sim 1$ Hz) plus standard (exponentially distributed) statistical fluctuations superimposed on the power law. The PDS slope and the break characterize the process randomly generating the diverse light curves of GRBs. Intriguingly, the PDS slope coincides with the slope of the Kolmogorov law. The power-law behavior is seen in individual bursts (we illustrate this in §3) and may provide a clue to the nature of GRBs.

In the present paper, we study in detail the PDSs of gamma-ray bursts. In our analysis, we use 527 GRB light curves with 64 ms resolution obtained by the Burst and Transient Source Experiment (BATSE) in the four Large-Area Detector energy channels, I–IV: (I) 20–50 keV, (II) 50–100 keV, (III) 100–300 keV, and (IV) $hv > 300$ keV. The background is subtracted in each channel using linear fits to the 1024 ms data.

The method of data analysis is described in §2. In §3, we study a sample of the four brightest and longest bursts. In §4, the average PDS for the full sample of 527 GRBs is calculated and discussed. In §5, we calculate the PDSs in the separate energy channels and quantify the difference of the temporal structure among the channels in terms of the PDS slope. We also calculate the autocorrelation function (ACF) in the separate channels and compare the results with previous studies of the ACF. In §6, we address dim GRBs and compare them to the bright ones. The results are discussed in §7.

2. DATA ANALYSIS

2.1. The Sample

Long bursts are of particular interest since their internal temporal structure can be studied by spectral analysis over a larger range of timescales. We choose bursts with durations $T_{90} > 20$ s, where $T_{90}$ is the time it takes to accumulate from 5% to 95% of the total fluence of a burst summed over all the four channels, I + II + III + IV. Hereafter, we measure the brightness of a burst by its peak count rate, $C_{\text{peak}}$, in channels II + III. We analyze bursts with $C_{\text{peak}} > 100$ counts per time bin, $\Delta t = 0.064$ s. This condition coupled with the duration condition, $T_{90} > 20$ s, gives a sample of 559 GRBs. The sample still contains GRBs with low fluence, which are not good for Fourier analysis. We exclude bursts with fluences $\Phi < 32C_{\text{peak}}$. The resulting sample contains 527 bursts.

2.2. PDS Calculation

We calculate the Fourier transform, $C_f$, of each light curve, $C(t)$, using the standard fast Fourier transform method. The power density spectrum, $P_f$, is given by $P_f = (C_f^* C_f + C_{-f}^* C_{-f})/2 = C_f^* C_f$ since $C(t)$ is real. The Fourier transform is calculated on a standard grid with a time bin $\Delta t = 64$ ms and a total number of bins $N_{\text{bin}} = 2^{14}$, which corresponds to a total time $T \approx 1048$ s since the trigger time. The light curve of each burst is considered in its individual time window $(t_1, t_2)$ (see §2.4). In the calculations of the PDS, we extend the time interval to $(0, T)$ by adding zeros at $(0, t_1)$ and $(t_2, T)$. Adding zeros introduces random small-scale fluctuations in the PDS (see, e.g., Bracewell 1965). We, however, study the PDSs averaged over adjacent frequencies and/or over a sample of GRBs. Then the random fluctuations in $P_f$ associated with a specific choice of the grid disappear and do not affect the results.

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2.3. The Poisson Level

Poisson noise in the measured count rate affects the light curve on short timescales and, correspondingly, affects the PDS at high frequencies. The Poisson noise has a flat spectrum, $P_f \propto f^0$, introducing the “Poisson level,” $P_\text{poisson}$, in a PDS. This level equals the burst total fluence including the background in the considered time window. The power spectrum above this level displays the intrinsic variability of the signal (but see § 4.2 for the time-window effects). We calculate the individual Poisson level for each burst and subtract it from the burst PDS.

2.4. The Time Window

One would like to see the whole burst in the window. However, (1) it is difficult to determine exactly the end of a burst because the burst can always have a weak “tail” hidden in the background and (2) the window should not be very large because inclusion of long weak tails leads to an increase of the background fluence, $\Phi_\text{background}$, without a substantial increase in the signal fluence, $\Phi$. The resulting low ratio $\Phi/\Phi_\text{background}$ implies a high Poisson level, which makes the quality of the PDS worse.

To reduce the Poisson level, we cut off the light curves at a time $t_2$ defined so that the signal count rate $C(t)$ does not exceed $\epsilon C_{\text{peak}}$ at $t > t_2$ and $C(t) = \epsilon C_{\text{peak}}$. Keeping in mind bursts with a weak beginning, we define the starting window time, $t_1$, so that $C(t) < \epsilon C_{\text{peak}}$ at $t < t_1$ and $C(t) = \epsilon C_{\text{peak}}$. In our analysis, $\epsilon = 0.05$ is chosen. We checked that varying $\epsilon$ does not significantly affect the results unless $\epsilon > 0.1$. Note that, for dim bursts, Poisson fluctuations of the background [which are imprinted on $C(t)$ even after subtraction of the average background level] may exceed $\epsilon C_{\text{peak}}$. Then the window $(t_1, t_2)$ is determined by the background fluctuations rather than by the signal.

3. INDIVIDUAL BRIGHT BURSTS

The brightest and longest bursts are the best ones for Fourier analysis. In this section, we study the four brightest bursts with $T_{90} > 100$ s. They have trigger numbers 2156 (GRB 930201), 2856 (GRB 940302), 3227 (GRB 941008), and 6472 (GRB 941110).
The light curves $C(t)$, summed over channels II and III, in which the signal is strongest. To simplify the comparison of different bursts, their Fourier transform $C_f$ is therefore normalized by and the PDS, is normalized

The presence of an underlying power law is an interesting feature of the GRB temporal behavior. A possible way to extract it from the noisy individual PDSs is to take the average PDS over a sample of long GRBs. Then the fluctuation of the GRB temporal behavior is given by a simple formula, $(11)$, where $N$ is the number of bursts in the sample. We refer to the peak radius of individual bursts. For comparison, we also plot the average PDS with the peak

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When comparing individual PDSs, $P_f$, with the peak-normalized $\bar{P}_f$, one sees that $P_f$ is exponentially distributed around $\bar{P}_f$ and the distribution is self-similar with respect to shifts in $f$.

The power-law fit to $P_f$ in the range $-1.4 < \log f < -0.1$ gives $\alpha \approx -1.75$ for the peak-normalized bursts and $\alpha \approx -1.67$ for $\sqrt{\Phi}$-normalized bursts. The formal error found from the $\chi^2$ fitting is very small, $\Delta x \sim \pm 0.01$ (we take the variance, $\Delta P_f/P_f = N^{-1/2}$). Note that the slope in the peak-normalized case is different from $-1.67$ reported in Beloborodov et al. (1998). This change is caused by the fact that we have extended the sample to smaller brightnesses (see §6).

The deviation from the power law at the low-frequency end is due to the finite duration of bursts. At the high-frequency end, there is a break at $-1$ Hz. The break is observed in the brightest GRBs even without subtracting the Poisson level (see Beloborodov et al. 1998 and Fig. 8, top panel). Note that the break position is the same for the peak-normalized and $\sqrt{\Phi}$-normalized bursts (see Fig. 3b). It stays the same in the separate energy channels (see Fig. 5) and does not depend on the Poisson level. One may also see the break in individual long bursts (Figs. 1 and 2). The break is far too sharp to be explained as an artifact of the 64 ms time binning, which suppresses the PDS by a factor of $[\sin(\pi\Delta t)/(\pi\Delta t)]^2$, where $\Delta t = 64$ ms is the time bin (cf. van der Klis 1989).

4.2. The Effects of Finite Signal Duration

Fourier analysis was designed for physical problems dealing with linear differential equations. For example, it is usually applied to small perturbations above a given background solution. The Fourier power spectrum is also commonly used in the temporal studies of long signals or noises, e.g., in persistent astrophysical sources. By contrast, GRBs have strongly nonlinear signals with short durations. The typical number of BATSE time bins ($\Delta t = 64$ ms) in a long GRB is a few times $10^3$. Do the effects of finite duration (i.e., time-window effects) strongly affect the measured PDS?
The issue is illustrated in Figure 4. We prepared an artificial long signal with $P_f \propto f^2$ and exponentially distributed $P_f$, i.e., the probability to detect $P_f$ at a given $f$ is proportional to $\exp(-P_f/P_f)$. The phase structure was taken to be Gaussian (i.e., random). The signal duration is $T_0 = 2^{11}\Delta t \approx 8400\, \text{s}$. Then we cut the long signal into 64 pieces of equal length $t_0 = 2^{14}\Delta t \approx 130\, \text{s}$. We thus get 64 short signals; each is a random realization/fragment of the same stationary process characterized by the index $\alpha$. Analogously to our analysis of real GRBs, we normalize each signal to its peak and add zeros up to $T = 2^{14}\Delta t$ (our standard grid). Then we calculate the average PDS, $\bar{P}_f$, for the 64 artificial signals. The result is shown in Figure 4 for the three cases: $\alpha = 0$ (Poisson), $\alpha = -1$ (flicker), and $\alpha = -5/3$ (Kolmogorov).

One can see that the time-window effects are strong in the case $\alpha = 0$. The Poisson signal is roughly constant on large timescales. As a result, at modest $f$, $\bar{P}_f$ is just the power spectrum of the $t_0$ window. By contrast, in the case $\alpha = -5/3$ we have large-amplitude variations in the signal on all timescales. The average PDS of the 64 short signals then reproduces well the intrinsic PDS slope throughout the whole range of frequencies, down to $f \sim t_0^{-1}$ (see Fig. 4, bottom panel). Hence, the power law we observe in the average PDS of GRBs can be interpreted to mean that GRBs are random short realizations of a standard process which is characterized by the PDS slope $\alpha \approx -5/3$. Note, however, that the power spectrum does not provide a complete description of the signal since the phase structure is not considered.

5. The PDS and the ACF in Channels I, II, III, and IV

What does the average PDS look like in the separate energy channels I, II, III, and IV? The signal-to-noise ratio is low in channel I and especially in channel IV. The number of GRBs for which good PDSs can be obtained in channels I–IV is therefore limited to the brightest bursts. We choose a sample of bursts with $C_{\text{peak}} > 500$ counts per bin (in channels II + III), which contains 152 bursts.

The burst analysis is now performed in each channel separately. We determine the Poisson level of a burst in each channel, $P_0$, and find the peak of the light curve, $C_{\text{peak}}$, where $i = I$, II, III, and IV. Then we perform the peak normalization: $C(t) \rightarrow C(t)/C_{\text{peak}}$ and $P_0 \rightarrow P_0/C_{\text{peak}}^2$. We set the time window in each channel $(t_1, t_2)$ as described in §2.4.

The resulting average PDSs in channels I–IV are shown in Figure 5. The differences in the slopes are clearly seen. We fitted the PDSs by power laws, $\log \bar{P}_f = A + \alpha \log f$, in the range $-1.6 < \log f < 0$. Channel IV is fitted in the range $-1.3 < \log f < -0.1$. Parameters $A$ and $\alpha$ of the fits are listed in Table 1.

The observed behavior can be briefly described as follows. The “red” power ($\bar{P}_f$ at low $f$) decreases at high photon energies and increases at low photon energies. It should be compared with the well-known fact that the pulses in a GRB are narrower in the hard channels (e.g., Norris et al. 1996). The hardness of emission varies dramatically during a burst and this leads to different temporal structure in different channels; e.g., pulses observed in the soft channels may be suppressed in the hard channels. One therefore could expect that the PDS has different slopes in different channels. Note that, typically, most of the GRB energy is released in channels II + III, and the average PDS of bolometric light curves approximately follows the $-5/3$ law.

In principle, the autocorrelation function (ACF) contains the same information as the PDS, since one is the Fourier transform of the other (the Wiener-Khinchin theorem). In

| Parameter | I    | II   | III  | IV   |
|-----------|------|------|------|------|
| $\alpha$  | -1.72| -1.67| -1.60| -1.50|
| $A$       | 1.03 | 1.05 | 1.06 | 1.07 |
practice, the two are not completely equivalent because of the time-window effects and the presence of a noisy background. On modest timescales, \( \lesssim 30 \) s, the direct ACF calculation and the calculation via the Fourier transform of the PDS give the same result to within a few percent (we have calculated the ACF by both methods). The average ACF, \( A(\tau) \), for our sample of 152 bright GRBs is shown in Figure 6 for each of the four channels. The ACF gets narrower at high energies, in agreement with previous studies (Fenimore et al. 1995), except that our ACF is \( \sim 2 \) times wider as compared to that obtained by Fenimore et al. (1995). The ACF width averaged over the channels is in approximate agreement with that calculated for the bolometric light curves by Stern & Svensson (1996).

Note that the average ACF is obtained by summing up the individual ACFs normalized to unity, i.e., \( A(0) = 1 \). Recalling that the ACF is the Fourier transform of the PDS, one can see that this normalization is equivalent to the normalization of the light curve by \( \sqrt{P_{\text{tot}}} \), where \( P_{\text{tot}} = \int [C(t)]^2 dt = \int P_\nu df \) is the total power. This normalization is different from the peak normalization we use in the calculations of the average PDS, i.e., we prescribe different weights to individual bursts when averaging the PDS and the ACF, respectively. Therefore, the average ACF is not the Fourier transform of the average PDS shown in Figure 5. This relation holds when the average PDS is calculated with the \( \sqrt{P_{\text{tot}}} \) normalization.

The ACF in each channel is perfectly fitted by the stretched exponential \( \tilde{A}(\tau) = \exp \left[ -(\tau/\tau_0)^\beta \right] \) (see Fig. 7). The parameters \( \tau_0 \) and \( \beta \) are listed in Table 2. The index \( \beta \) is related to the PDS slope \( \alpha \) by the simple relation \( \beta \approx - (1 + 2\alpha) \).

The changing \( \beta \) demonstrates that the ACF shape changes from channel to channel, as it should do since the PDS changes. As a first approximation, the PDS slope is equal to \( -5/3 \), and the ACF index \( \beta \approx 2/3 = 5/3 - 1 \).

The values of \( \tau_0 \) quantify the ACF width in different channels. The parameter \( \tau_0 \) is better defined as compared to measuring the ACF width at a certain level, e.g., at \( e^{-0.5} \) of the maximum level, as done in Fenimore et al. (1995). Nevertheless, the scaling of \( \tau_0 \) with energy is approximately the same, \( \tau_0 \propto E^{-0.4} \), where \( E \) is the photon energy of the low-energy boundary of the channel (see Fenimore et al. 1995). It should be stressed, however, that the stretching of \( \tau_0 \) is not related to the stretching of any physical timescale of intrinsic correlations during the burst. The ACF width, \( \tau_0 \), is rather related to the position of the breaks in the PDS, especially the low-frequency break, which in turn is determined by the burst duration. For an infinitely long signal with a power-law PDS, \( \tau_0 \) would tend to infinity. This is natural since the power-law behavior implies self-similarity, i.e., the absence of any preferred timescale. Specific timescales are introduced only by the breaks in the PDS. We therefore have only two physical timescales in long GRBs: the first one is associated with the 1 Hz break, and the second one is associated with the low-frequency break due to the finite burst duration.

6. DIM VERSUS BRIGHT BURSTS

Now we address the following question: Is there any correlation between the PDS slope and the burst brightness?

6.1. PDS Slope Correlates with the Burst Brightness

We take the full sample of 527 light curves in channels II + III and divide it into three groups of different brightnesses: (A) \( C_{\text{peak}} > 800 \), (B) \( 300 < C_{\text{peak}} < 800 \), and (C) \( 100 < C_{\text{peak}} < 300 \). Group A contains 91 bursts, group B 222 bursts, and group C 214 bursts. We have calculated the

![Fig. 6.—Average autocorrelation function for the sample of 152 bright bursts, in channels I–IV.](image-url)

![Fig. 7.—Average ACFs in channels I–IV are plotted against \( \tau^\beta \), which should give a straight line for a stretched exponential.](image-url)

| Parameter | I   | II  | III | IV  |
|-----------|-----|-----|-----|-----|
| \( \beta \) | 0.73| 0.67| 0.63| 0.6 |
| \( \tau_0 \) | 14.0| 10.7| 7.3 | 5.1 |
average PDS for each group separately employing the peak normalization. The results are presented in Figure 8. We fitted the average PDSs by power laws, $\log P_f = A + \alpha \log f$. The parameters $A$ and $\alpha$ of the fits in the range $-1.5 < \log f < -0.1$ are listed in Table 3. We conclude that the average PDS of dim bursts gets markedly steeper.

6.2. Subtraction of the Poisson Level

In the PDS calculations, we subtracted the Poisson level, which is quite high for dim bursts (see Fig. 8). One therefore should address a technical question: How well is the intrinsic PDS restored after subtracting the Poisson level?

To investigate this issue, we have performed the following test. We take the sample of 91 bright bursts (group A) and add a strong Poisson noise (with an average level of 25,000 counts per bin) to each burst in the group. We thus artificially increase the Poisson level by 2 orders of magnitude. Alternatively, one may consider this procedure as a rescaling of bright bursts to a smaller brightness while keeping the Poisson background at the same level. Then we analyze the artificial bursts in the same way as we did with the real dim GRBs. Note that even after subtraction of the time-averaged background, the background Poisson noise strongly affects the signal and may create artificial peaks dominating the true peak of the signal. For the artificial bursts, we know the true peak (which is the peak of the original bright burst). In real dim bursts, we do not know the position of the true peak and employ the peak search scheme described in Stern, Poutanen, & Svensson (1999).

The result is compared with the average PDS of the original sample in Figure 9. We find that the subtraction of the Poisson level allows one to restore the original PDS, $P_f$, also at frequencies where $P_f$ is well below the Poisson level. Even the 1 Hz break remains present. We conclude that the high Poisson level is unlikely to significantly affect the measured PDS slope.

7. DISCUSSION

7.1. Relation to the Average Time Profile

The average time profile (ATP) of GRBs was found to follow a stretched exponential of index 1/3 (Stern 1996). Is there any relation between the ATP and the average PDS? One should note two important differences between the

![Figure 8](image)

**Fig. 8.**—Average PDSs for the three brightness groups A, B, and C. Dashed lines show the power-law fits (see Table 3). Solid lines show the Poisson level.

| Parameter | A   | B   | C   |
|-----------|-----|-----|-----|
| $\alpha$  | -1.63 | -1.74 | -1.82 |
| $A$       | 1.04 | 0.98 | 0.91 |

![Figure 9](image)

**Fig. 9.**—Average PDS of 91 artificial dim bursts created from group A of the brightest bursts (see Fig. 8). Solid histogram: The original PDS for group A. Dashed and dotted histograms: The average PDS of the artificial bursts with and without subtraction of the Poisson level, respectively. Solid lines: Average Poisson levels for the original and the artificial bursts, respectively.
ATP and the PDS studies: (1) the $-5/3$ PDS, though affected by the statistical fluctuations, is observed in individual bursts, while the ATP is a purely statistical property of a large sample of bursts and (2) the ATP is constructed for GRBs of all durations (and only in this case it displays the perfect stretched exponential), while the PDS is studied for long bursts only. Nevertheless, both the ATP and the PDS characterize the stochastic process generating GRBs. Stern (1999) shows that both can be reproduced simultaneously with the pulse-avalanche model of Stern & Svensson (1996).

7.2. The 1 Hz Break

The sharpness of the break in the average PDS appears to be an important feature that constrains models of GRBs. If the signal is produced in the rest frame of a relativistic outflow, then variations of the outflow Lorentz factor, $\Gamma$, from burst to burst would smear out the break. The sharpness of the break then implies a narrow dispersion of $\Gamma$, $\Delta \Gamma/\Gamma \leq 2$, which appears to be unlikely.

Alternatively, the GRB variability may come from the central engine. The break in the PDS might then be related to a typical timescale, $\sim 1 \text{s}$, in the central engine.

Finally, one may associate the break with the dynamical timescale corresponding to the inner radius of the optically thin zone of the outflow, $R_\text{in}$. Then the variability on timescales shorter than $\tau_\text{s} = R_\text{in}/c\Gamma^2$ can be suppressed. In this case, however, one should explain why $\tau_\text{s}$ stays the same in different bursts.

7.3. Dim GRBs

It has often been hypothesized that dim bursts are at high cosmological redshifts. For instance, it is necessarily the case if GRBs have approximately the same intrinsic luminosity, the so-called “standard candle” hypothesis. We can test this hypothesis using the power spectrum analysis.

Suppose that the dim bursts are intrinsically the same as the bright ones. Then any difference in their average PDS should be due to a cosmological redshift. First consider the bolometric light curves, assuming that their average PDS follows the $-5/3$ power law. It is easy to see that a redshift, $z$, will not change the PDS slope. As we normalize each burst to its peak before the averaging, the effect of a redshift is just stretching the light curve in time, i.e., precisely the time dilation effect. This will lead to an increase of the net normalization of the PDS by a factor of $(1+z)^{1/3}$. The slope does not change since the dilation factor $(1+z)$ is the same for each timescale.

One should, however, recall that we observe bursts in a limited spectral interval. A redshift then implies a shift of the signal with respect to our spectral window; e.g., photons detected in channel III would originally have been emitted in channel IV. As we know from § 5, the PDSs are different in different energy channels. Therefore, one expects that the PDS slope will change for redshifted GRBs.

We have seen in § 5 that the PDS of bright bursts flattens in the hard channels. Hence, a redshift of the bright bursts must be accompanied by a flattening of the PDS. Contrary to this behavior, we observe that the PDS of dim bursts steepens. Hence, the evolution of the PDS with brightness is inconsistent with the standard candle hypothesis. It implies that the burst luminosity function is broad and dim bursts are intrinsically weak.

Evidence for a broad luminosity function is also found when looking at the isotropic luminosities of the bursts with measured redshifts. Note, however, that the differences in the apparent luminosities could be caused by orientation effects if GRBs are beamed. One should not therefore exclude that the total intrinsic luminosities are approximately the same. The different temporal structure of dim bursts may be an important fact in this respect. In particular, it suggests that the observed time dilation of dim bursts (e.g., Norris et al. 1994) may be caused mainly by physical processes occurring in the bursts rather than by a cosmological redshift. Note that the intrinsic difference of the temporal structure of dim GRBs was also found when studying their average time profile (see Stern, Poutanen, & Svensson 1997). The rising part of the ATP does not change with decreasing brightness while the decaying part suffers from time dilation. This behavior is inconsistent with a cosmological time dilation which should apply equally to both parts of the ATP.

7.4. Internal Shocks

A likely scenario of GRBs involves internal shocks in a relativistic outflow with a Lorentz factor $\Gamma \sim 10^2$ (see, e.g., Piran 1999 for a review). The shock develops when an inner faster shell of the outflow tries to overtake the previous slower shell. The pulses in a burst are then associated with collisions between the shells. The PDSs predicted by the model were recently tested against the observed $-5/3$ law (Panaiteanu, Spada, & Mészáros 1999; Spada, Panaiteanu, & Mészáros 2000; Beloborodov 1999, 2000). The self-similar temporal structure with $\alpha = -5/3$ can be reproduced by the model. Further constraints should, however, be imposed by the observed dependence of $\alpha$ on photon energy. Besides, the phase structure of the signal, neglected so far, should be taken into consideration (Beloborodov 2000).

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