TEMPORAL VARIABILITY OF GAMMA–RAY BURSTS*

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Dedicated to Andrzej Białas in honour of his 60th birthday

We apply the method of scaled factorial moments to the analysis of temporal variability of gamma–ray bursts. Using this method we are able to estimate for majority of long bursts their characteristic variability scale, which we call pulse duration time T_P. This new scale is independent from burst duration time introduced earlier and for most bursts in our sample is of order of 1.5 s. We find also that the average T_P for a group of very bright bursts is a factor of 2 shorter than that of dim bursts. This seem to support the hypothesis on cosmological nature of gamma–ray burst sources.

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1. Introduction

Gamma–Rray Bursts (GRB) remain among the most mysterious phenomena on the sky. A quarter of a century after their discovery [1] the nature of and distance scale to their sources is still an open question and is currently the subject of a "great debate" in the astronomical community [2, 3]. One of most important reasons of this situation is the fact that we know no quiescent counterparts of the bursts at any range of electromagnetic spectrum. Therefore we can not establish any link between bursts

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and other astronomical objects and use the power of ground-based and space-based telescopes to study the nature and distance-scale of GRBs.

Recently, the Burst and Transient Source Experiment (BATSE) on board of Compton Gamma-Ray Observatory has provided important, qualitatively new data on bursts distribution on the sky, their temporal and spectral properties. These data show [4] that the sky distribution of GRB is isotropic but not homogeneous demonstrating deficiency of dim bursts relative to homogeneous Euclidean case. It means that either number density of GRSs is reduced at large distances or the space in which they are distributed is non-Euclidean. Such distribution is inconsistent with the distribution of any objects which are known to be in our galaxy (like stars or globular clusters). If we want to reconcile the hypothesis on galactic origin of GRBs with the data we have to assume that they originate from Galactic "corona" — a new, previously unknown type of extended galactic halo [2]. On the other hand this distribution is naturally explained if GRBs originate from cosmological sources [5, 6, 3]. If this is the case, than the faint bursts should be redshifted, making their duration longer and their spectra softer [7, 8]. Recently reported time dilation in faint BATSE bursts [9, 10] (but see also [11]) seem to support this hypothesis. This results were obtained from studies of temporal properties of GRBs.

Temporal properties of GRBs were studied for some time already. In BATSE catalog [12] the main parameter describing temporal characteristics of a burst is its duration time T_{90} (T_{50}) defined as a time during which the integrated counts increase from 5% to 95% (25% to 75%) above background. The distribution of burst duration times is bimodal [13], *i.e.* burst population can be separated into two classes: short events ($T_{90} < 2$ s) and longer ones ($T_{90} > 2$ s). Similar result was obtained earlier for pre-BATSE data [14]. Most burst show an asymmetry [15, 16] — their rise is more rapid than the decay. Another general property of GBRs time profiles is that the duration of individual pulses within a burst depends on the energy with peaks becoming narrower at higher energies [15, 17]. It was also shown [18] that for bursts with multiple pulses later spikes tend to be softer than earlier ones.

Although we do not know the mechanism in which photons are produced at the GRB source, one can assume that the resolution of a burst into individual pulses corresponds to the decomposition of full production process into more elementary subprocesses. Thus the duration time of a single pulse should better characterize the mechanism of photon production than the duration time of a whole burst. From that point of view it would be useful to have the estimates of pulse duration times for a large group of bursts. In addition, if GRBs are at cosmological distances, than time dilation should be observed on all timescales. Therefore pulse duration time should be as good indicator of cosmological signature as burst duration time.

The aim of this paper is to obtain estimates of pulse duration times for a large, selected in a intensity–independent way group of GRBs and to analyze the resulting distribution. In particular we will compare the distribution of pulse duration times for bright and dim bursts to check whether time dilation effects are visible. To get a estimate of pulse duration time we will use a method based on a scaled factorial moments introduced by Białas and Peschanski [19, 20].

2. The method

We apply our analysis to the temporal data of GRBs available in Compton Observatory Science Support Center public archive. For each burst we use its time profile recorded from BATSE's large–area detectors with 64 ms resolution (BATSE PREB + DISCSC data types). BATSE large–area detectors register the data in four energy channels set approximately: 20–50 keV, 50–100 keV, 100–300 keV and > 300 keV. We use the time profiles summed over all energy channels. Each profile covers $\sim$ 2 s before burst trigger (PREB data) and at least $\sim$ 240 s after (DISCSC data).

In this paper we work only with long bursts, *i.e.* those with duration time $T_{90} > 10$ s. The method we are using is sensitive to the shape of time history of GRB. To avoid signal contamination we take into account only those bursts which did not overwrite an earlier and were not overwritten by a later bursts. At the time this analysis was performed there were 309 such bursts available in BATSE archive.

The main difficulty in determining the pulse duration time is a very complex structure of many multi–peaked bursts and wide range of shapes of peaks in bursts profiles. The method we use consists in studying the dependence of scaled factorial moments [19, 20] of time profile of a burst as a function of scale at which this profile is binned. Scaled factorial moments were widely used for studying correlations in multiparticle production at high energies [21, 22], description of fluctuations in phase transitions in Ising model [23, 24] or analysis of spatial distribution of galaxies [25]. Using this method we neither make any assumption on the shape of the burst, nor subtract the background.

Let us consider a fragment of a burst history of a length T. It is represented as a time series of $N_0 = T/d_0$ elementary bins with ultimate resolution $d_0 = 64$ ms. To probe this part of a burst with time resolution d, a multiple of d_0, we take N bins of width d. Each such bin consists of $n_d = d/d_0$ consecutive elementary bins starting with elementary bin number l, where l is a whole random number between 1 and $N_0 - n_d + 1$. By

k_n we denote the number of photons registered in $n - th$ bin. The $i - th$ scaled factorial moment is defined as follows:

$$F_i = \frac{N^{i-1}}{K(K-1)\ldots(K-i+1)} \sum_{n=1}^{N} k_n(k_n-1)\ldots(k_n-i+1)\,, \qquad (1)$$

where

$$K = \sum_{n=1}^{N} k_n\,.$$

For each burst we take into account available in archive part of burst history between $T_{90}^S - T_{90}/2$ and $T_{90}^S + 3 \times T_{90}/2$. Here by T_{90}^S we denote the start time for T_{90} interval, as defined in BATSE duration table.

We calculate the factorial moments F_i, $i = 2\ldots5$ of time profile as a function of resolution from lowest resolution $d_L \sim T/2$ up to the highest available resolution d_0. To find the temporal scale corresponding to the pulse duration time we analyze the logarithm of moments as a function resolution, *i.e.* $-\ln(d)$. As long as the structure of the burst is not resolved, the moments grow with improving resolution (decreasing d). For resolutions finer then the scale of burst structure the moments should not depend on the resolution. The time scale at which the burst is resolved corresponds to the "knee" in log–log plot at which the moments stop growing and become flat. To determine this time scale we apply the following algorithm. For a given moment we consider all resolution points for which $\ln(F_i) < 0.95\ln(F_i(d_0))$. We use these points to define a straight line approximating flat part of $\ln(F_i)$ vs. $-\ln(d)$ dependance. The scale d_i at which burst is resolved is defined as a resolution for which data points deviate (are lower) from the line defined above by 2.5 %. We want the "knee" feature to be a significant division point between rising and flat part of moment vs. resolution curve. To assure this we will demand the slope of line approximating the flat part of $\ln(F_i)$ vs. $-\ln(d)$ dependance to be at least 5 times smaller than the slope of a line between maximal and minimal value of F_i. In principle different moments may point to different characteristic time scales. In this study we will consider only those bursts for which the characteristic time scales as defined by different moments do not differ very much requiring that the maximal difference of logarithms of scale obtained from different moments is less then 0.3 (which corresponds to the maximal difference in scales < 35 %). If for some burst one of the above requirements is not fulfilled we will treat such burst as unresolved.

For resolved burst the time T_P is defined as follows:

$$\ln(T_P) = \sum_{i=2}^{5} \ln(d_i)/4\,. \qquad (2)$$

An example of determination of pulse duration time for the burst with trigger number 1200 is given in Fig. 1. In this figure a way of estimating the scale d_5 by means of fifth moment is demonstrated. The value of $\ln(d_5)$ obtained here equals 1.582, which corresponds to the value of scale $d_5 =$ 4.865 s. If we take all four moments into account, using equation (4) we obtain that $\ln(T_P) = 1.575$ and therefore $T_P = 4.831$ s.

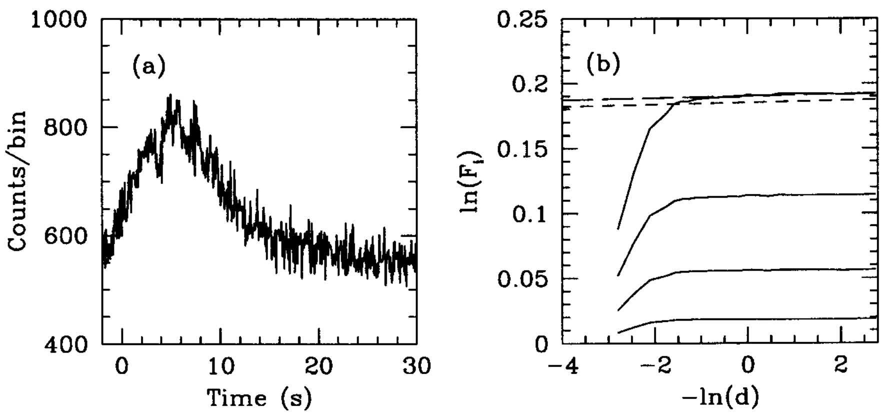

Fig. 1. Determination of T_P for burst with BATSE trigger number 1200. (a) — Total counts per time bin summed over all energy channels. (b) — Solid lines: natural logarithms of second, third, fourth and fifth moment vs. natural logarithm of resolution expressed in seconds. The subsequent moments are labeled by their moment number. Long dashed line – fit to the flat part of $\ln(F_5)$ vs. $\ln(d)$ dependence. Short dashed line shows 2.5 % deviation from that fit. d_5 is defined as a resolution at which the data cross short dashed line.

3. Results

We apply the method described in previous section to the sample of 309 long ($T_{90} > 10$ s) bursts from BATSE archive. For 43 bursts the moments vs. resolution dependence is not flat for high resolution. For 12 out of those bursts this dependence is rising in whole resolution domain — clearly those bursts have $T_P < 64$ ms. From the remaining 31 events in this group in 24 cases one can observe clear flat plateau at higher resolution, only the last point is slightly rising. We ignore this last point and take those 24 bursts into further considerations. For 7 bursts the rising part after plateau is visible for 2 or more last points, so we regard those burst as unresolved. As a result in first part of analysis we obtain 290 bursts for which a plateau at high resolutions can be observed. However, only in 201 events additional requirements formulated in previous section are fulfilled, so we treat only those 201 bursts as resolved. We conclude, that our method works for majority of bursts in our sample — we resolve 65 % of events.

The distribution of values of T_P for resolved burst is shown in Fig. 2. This figure shows that for most of the burst their variability is not very strong — the peak of this distribution is around $T_P = 2.0$ s, with 69 % of resolved bursts having $T_P > 1$ s. We did not measure T_P for short bursts, but the shape of distribution in Fig. 2 and the fact, that short bursts have narrow pulses [26] may suggest that the T_P distribution for the whole BATSE sample will be bimodal, like T_{90} distribution.

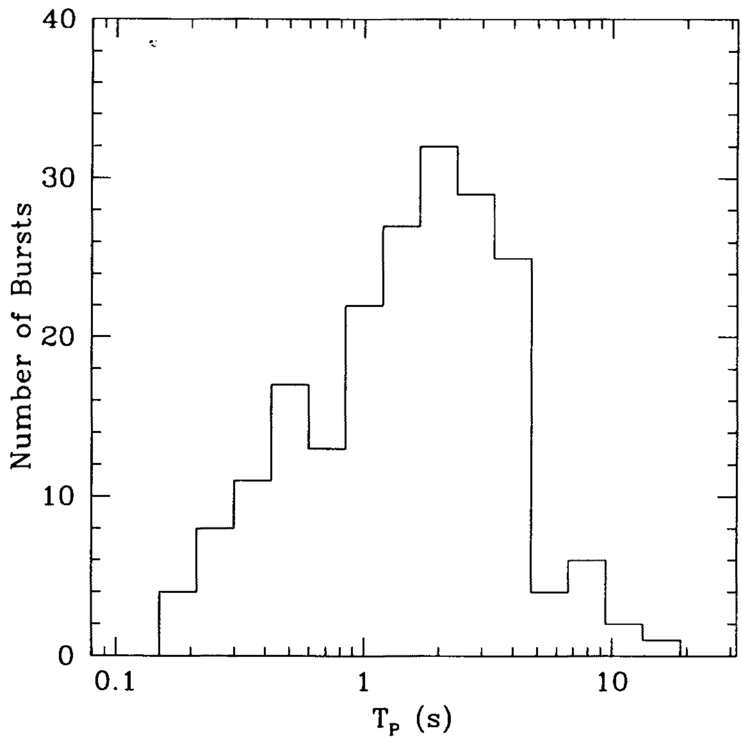

Fig. 2. T_P duration distribution for the sample of resolved long bursts.

We find that the correlation between burst duration time T_P and pulse duration time T_{90} is very weak. This can be seen in Fig. 3, where T_P — T_{90} scatterplot is shown. Lack of strong correlation may be understand if we note, that many long bursts are multipeaked, *i.e.* they are long because they consist of many peaks. There are also bursts for which their burst activity is concentrated in two or more episodes well separated in time. Thus we may have long burst made of short pulses. On the other hand in analyzed sample there are burst which contain only single, broad peak.

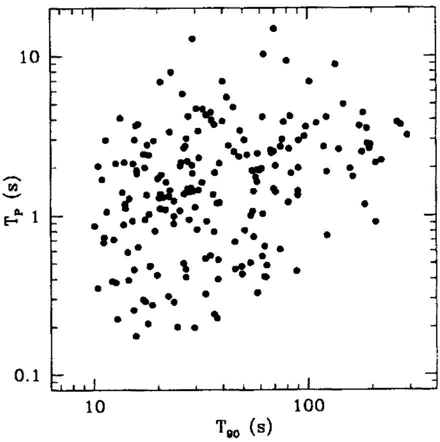

Fig. 3. T_P — T_{90} scatterplot for sample of 201 resolved bursts.

If the bursts are at cosmological distances, then the time profiles of distant sources should be dilated relative to nearer ones [7, 8]. Such time dilation of burst duration was reported recently [9, 10]. If this is really the case, we should observe similar effect in T_P distribution. We have to stress, that in such analysis we do not know the distances to the GRB sources and take burst luminosity as a distance indicator. We take two well separated in luminosity groups of GRBs and compare average T_P calculated for them. As a measure of burst luminosity we take the peak flux on 256 ms scale f_{P256}, as defined in BATSE flux table. In this comparison dim bursts are bursts with $f_{P256} < 0.5$ photons/cm^2 s, whereas bright are those with $f_{P256} > 4.0$ photons/cm^2 s. The resulting T_P distributions for both groups are shown in Fig. 4. It is clear from this figure, that these distributions are different. This observation is quantitatively confirmed by result of Kolmogorov–Smirnov two sample test [27]: probability that they are in fact identical is 4.96×10^{-3}.

If we define a dilation factor as a ratio of average value of T_P for dim and bright bursts, we obtain for the value of this factor 2.26 ± 0.61 if we average times or $2.53^{+0.77}_{-0.59}$ if we average logarithms of times. This value of dilation factor is consistent with values obtained previously in [9, 10]. It means, that if cosmological effects are responsible for the difference of duration times of dim and bright bursts then dim bursts originate from sources located at $z \geq 1$.

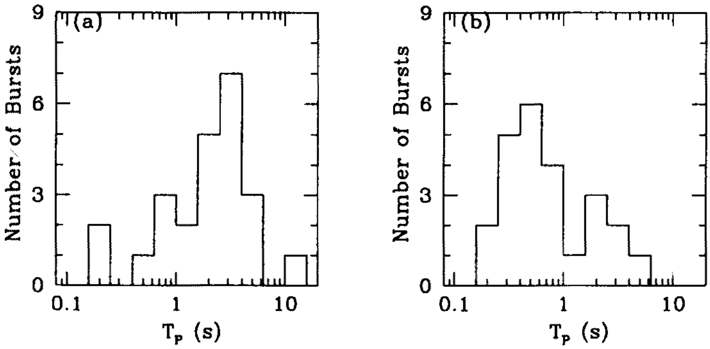

Fig. 4. T_P duration distribution for group of (a) — 24 dim and (b) — 24 bright BATSE bursts chosen from resolved long burst sample.

4. Conclusions

We propose a new method of analysis of temporal properties of gamma ray burst which consists in studying how the scaled factorial moments of burst time histories depend on resolution. This method allows us to attribute the burst a new characterizing time scale which we call pulse duration time T_P. We apply this method to the sample of 309 long ($T_{90} \geq 10\,s$) bursts from BATSE public archive. For majority of bursts (65 %) the method was successful. The variability of resolved bursts from analysed sample is not very strong. The peak of T_P distribution is around $2\,s$, with 69 % of resolved events having $T_P \geq 1\,s$. On the other hand at least in case of 12 bursts their variability scale is less than $64\,ms$, *i.e.* our ultimate time resolution.

We compare also average values of T_P for two well separated in luminosity groups of gamma ray bursts and find that the value for dim bursts is a factor of 2 higher than respective value for bright bursts. As we expect that dim bursts come from much more distant sources than bright ones, this result seems to support the hypothesis on cosmological nature of burst sources. In that case more distant sources are stretched in time due to cosmological redshift.

Cosmological redshift should change not only temporal but also spectral properties of GRBs – dim burst should have lower peak energy than bright ones. Such effect was in fact reported recently [28]. It would be interesting to perform joint analysis of temporal and spectral properties of bursts and check whether they are simultaneously consistent with hypothesis of their cosmological origin.

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