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# Classification of gamma-ray bursts observed with Konus-Wind

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**Abstract.** We present the analysis of duration and spectral-hardness distributions of  $\sim 3000$  gamma-ray bursts (GRBs) detected by Konus-Wind (KW) between November 1994 and early February 2019. We analyse burst  $T_{50}$  and  $T_{90}$  durations (the time intervals which contain the central 50% to 90% of the total burst count fluence, respectively) and argue that  $T_{50}$  is more robust duration measure than  $T_{90}$ . Using a two log-normal component fit to the  $T_{50}$  distribution we pick the boundary between the overlapping classes of short-duration and long-duration bursts to be at  $T_{50} = 0.7$  s, which implies the fraction of short GRBs ( $T_{50} < 0.7$  s) to be  $\sim 17\%$ . Using Gaussian mixture model fits we show that hardness-duration distribution can be well described by three Gaussian components, with two components corresponding to short/hard and long/soft GRB population, and the third component covering the softest GRBs with intermediate durations. This classification suggests that  $\sim 14\%$  KW GRBs are from short/hard population.

Finally we discuss a possibility to discriminate between physically distinct Type I and Type II GRBs with the help of hardness-duration distribution.

## 1. Introduction

Gamma-ray bursts (GRBs) can be divided into two overlapping morphological classes based on the properties of the observed gamma-ray emission: short/hard GRBs, with a duration  $\lesssim 2$  s, have hard prompt-emission spectra and negligible spectral lag, and long/soft GRBs with a duration typically  $\gtrsim 2$  s, have softer spectra and non-negligible spectral lag [1, 2, 3].

The long/soft and short/hard bursts are believed to have different physical origins. Short/hard GRBs are considered to be the results of mergers of binary compact objects (so called Type I GRBs), such as two neutron stars or a neutron star and a black hole (see, e.g. [4] and references therein), while long/soft (Type II GRBs), which are occasionally accompanied by supernovae, originate from the core collapse of massive stars, see [5] for more information on the Type I/II classification scheme.

The Konus-*Wind* gamma-ray burst spectrometer (hereafter KW, [6]) has observed  $\sim 3000$  GRBs, with  $\sim 500$  of them being short GRBs, in the period from launch in 1994 to early 2019, which is the largest set of GRBs observed with a single instrument to date over a broad energy band. Here, we present the burst duration, hardnesses and its classification.

We start with a description of the KW detectors and its GRB sample in Section 2. In Section 3 we describe the analysis procedures and present the results. Finally, in Section 4 we conclude with a summary.

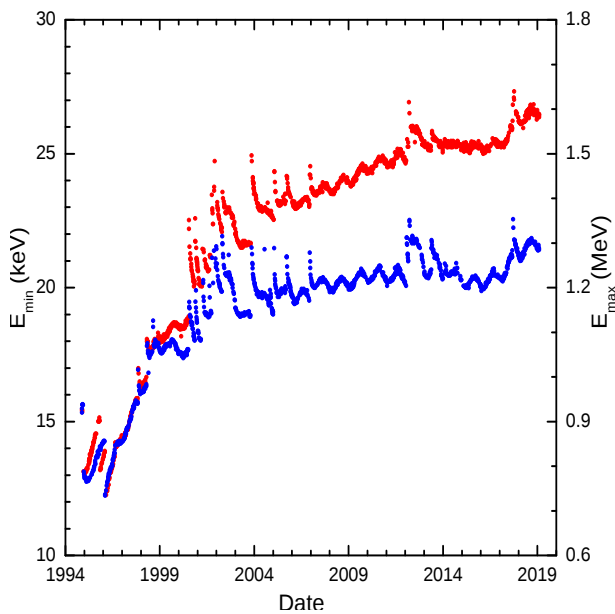


## 2. Konus-WIND

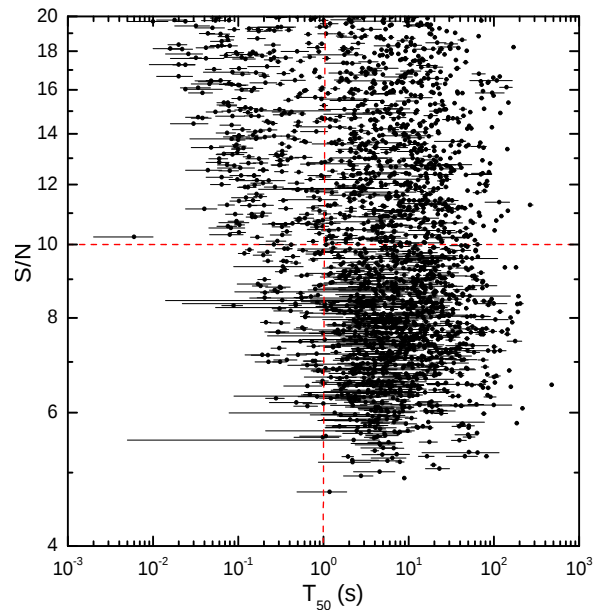
KW consists of two identical NaI(Tl) detectors S1 and S2, each with  $2\pi$  field of view. The detectors are mounted on opposite faces of the rotationally stabilized *Wind* spacecraft (launched on 1994 November 1), both observing the whole sky. Each detector has an effective area of  $\sim 80\text{--}160\text{ cm}^2$  depending on the photon energy and incident angle. The nominal energy range of gamma-ray measurements covers the incident photon energy interval from 13 keV up to 10 MeV.

The instrument has two operational modes: waiting and triggered. While in the waiting mode, the count rates are recorded in three energy bands G1 (13–50 keV), G2 (50–200 keV), and G3 (200–760 keV) with 2.944 s time resolution. When the count rate in the G2 band exceeds a  $\approx 9\sigma$  threshold above the background on one of two fixed time-scales, 1 s or 140 ms, the instrument switches into the triggered mode. In the triggered mode, the count rates in the three energy bands are recorded with time resolution varying from 2 ms up to 256 ms. These time histories, with a total duration of  $\sim 230$  s, also include 0.512 s of pre-trigger history. Spectral measurements are carried out, starting from the trigger time  $T_0$ , in two overlapping energy intervals, PHA1 (13–760 keV) and PHA2 (160 keV–10 MeV). After the triggered-mode measurements are finished, KW switches into the data-readout mode for  $\sim 1$  hr with no measurements available for this time interval. For a more detailed description of KW see [7, 8].

The detector energy scale is calibrated in-flight using the 1460 keV line of  $^{40}\text{K}$  and the 511 keV annihilation line. The gain of the detectors has been slowly decreasing during the long period of operation. The instrumental control of the gain became non-functional in 1997 and the spectral range shifted from the nominal to 25 keV–18 MeV for the S1 detector and to 20 keV–15 MeV for the S2 detector; the G1, G2, G3, PHA1, and PHA2 energy bounds changed accordingly, see figure 1.



**Figure 1.** Evolution of Konus-*Wind* energy boundaries of the S1 (red) and S2 (blue) detectors.  $E_{\min}$  is the lower bound of G1 and  $E_{\max}$  is the upper bound of G3.



**Figure 2.**  $S/N$ - $T_{50}$  distribution of KW GRBs. The horizontal dashed line corresponds to  $S/N = 10$  and the vertical dashed line denotes  $T_{50} = 1$  s.

### 3. Data analysis and results

We analyzed 2977 triggered GRBs detected between the 1994 November 17 and the 2019 February 6, hereafter the full sample.

#### 3.1. Burst durations

The total burst duration  $T_{100}$ , and the  $T_{90}$  and  $T_{50}$  durations (the time intervals that contain 5% to 95% and 25% to 75% of the total burst count fluence, respectively [2]), were determined in this work using the lightcurves in G2+G3 energy band ( $\sim 80$ – $1200$  keV at present).

The burst durations are computed using a concatenation of waiting-mode and triggered-mode light curves with a method similar to that developed for BATSE [9]. The burst's start and end times are determined by searching an excess above background on timescales from the best available lightcurve resolution up to 100 s in the interval from  $T_0 - 250$  s to  $T_0 + 240$  s. The background is approximated by a constant, using, typically, the interval from  $T_0 - 2500$  s to  $T_0 - 250$  s. For each burst we calculated  $T_{100}$ ,  $T_{50}$ , and  $T_{90}$  at three confidence levels,  $4\sigma$ ,  $5\sigma$ , and  $6\sigma$ . The  $1\sigma$  significance is defined as the square root of the background counts accumulated over the interval of interest with background value uncertainty added in quadrature.

Because of the trigger criteria described in section 2, weak short-duration bursts are significantly undersampled. The  $S/N$ – $T_{50}$  distribution (figure 2) shows a lack of short  $T_{50} \lesssim 1$  s weak GRBs with signal-to-noise ratio  $S/N < 10$ . The  $S/N$  is the detection significance measured in G2 over the 64 ms peak count rate interval. To account for this bias we selected a subsample of 1841 GRBs with  $S/N \geq 10$ , hereafter the unbiased sample.

We have fitted the  $\log T_{50}$  and  $\log T_{90}$  distributions with a mixture of one-dimensional Gaussian components using the Expectation-Minimization algorithm provided in scikit-learn Python package [10]. The algorithm maximizes the log-likelihood

$$L = \sum_i \ln p(x_i), \text{ where } p(x) = \sum_l p(x|l)p_l, \text{ and } p(x|l) = \frac{1}{\sqrt{2\pi}\sigma_l} \exp\left(-\frac{(x - x_{cl})^2}{2\sigma_l^2}\right), \quad (1)$$

where  $p_l$  is the weight of the  $l$ -th component in the mixture (all the  $p_l$  sum to one),  $p(x|l)$  is a conditional probability density assuming that a burst belongs to the  $l$ -th component,  $\sigma_l$  is the component width,  $x_{cl}$  is the component centroid, and  $x = \log T$ .

We have used the likelihood ratio to test whether an additional component significantly improves the fit. The distribution of  $-2(L_N - L_{N+1})$ , where  $N$  is the number of components, is asymptotically  $\chi_3^2$  and  $\chi_6^2$  in one and two dimensional cases, respectively (see e.g., [11]). The parameter errors were estimated using Monte-Carlo sampling from the observed data.

Results of the fits with  $N = 2$  are presented in tables 1 and 2 (errors are given at 68% confidence level). We found, that adding a third log-normal component does not significantly improve the fits for the  $\log T_{50}$  distributions, with the maximum  $-2\Delta L \sim 3$  (which corresponds to a probability  $P \sim 39\%$  that the fit improvement occurs by chance). For all the  $\log T_{90}$  distributions  $-2\Delta L > 25$  ( $P \lesssim 10^{-5}$ ), which favors three-component fit, with one component corresponding to the short GRB distribution and two to the skewed distribution of long GRBs. The  $T_{50}$  distribution parameters show less variation with the search threshold, as compared to those of the  $T_{90}$  distributions; in particular, the variation of the long GRB component centroid is smaller by a factor of  $\sim 2$ ; thus implying  $T_{50}$  to be a more robust burst duration measure. Therefore we decided to use  $T_{50}$  (calculated using the  $5\sigma$  threshold) for KW GRB classification and defined the boundary between short and long bursts as the intersection point of the two Gaussian components  $T_{50\text{int}}$ .

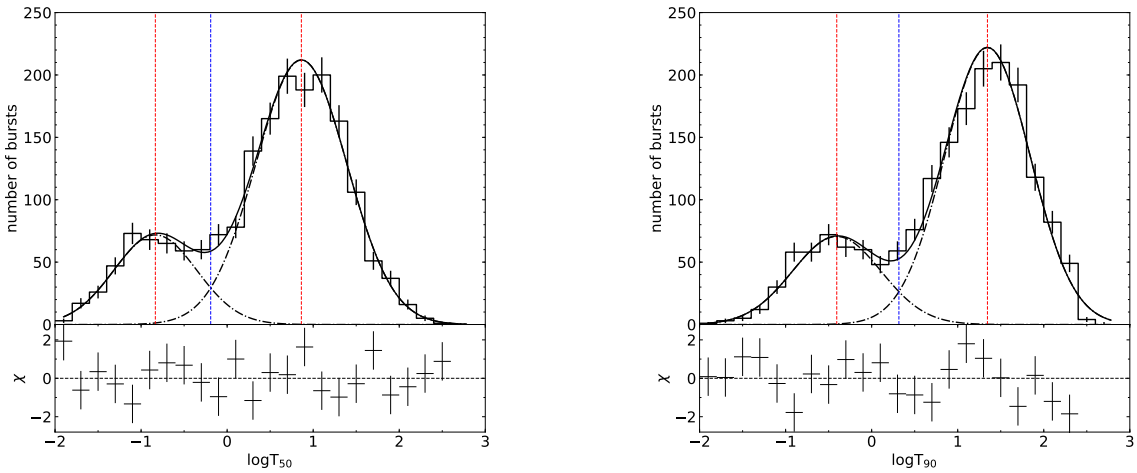
For the unbiased sample  $T_{50\text{int}} = 0.7$  s and the fraction of short bursts with  $T_{50} < 0.7$  s is  $\sim 24\%$  ( $\sim 14\%$  for the full sample). About 8% of the short bursts may originate from the short-duration tail of the long GRB population. The selected boundary between long and short bursts is consistent with one used to select the sample for the second KW short GRB catalog [7].

**Table 1.**  $T_{50}$  distribution parameters.

| Sample   | Significance level ( $\sigma$ ) | $p_1$                | $T_{50c1}$<br>s        | $\sigma_1$                | $p_2$                | $T_{50c2}$<br>s        | $\sigma_2$                | $T_{50int}$<br>s       | $L$     |
|----------|---------------------------------|----------------------|------------------------|---------------------------|----------------------|------------------------|---------------------------|------------------------|---------|
| full     | 4                               | $16.1^{+0.7}_{-0.6}$ | $0.18^{+0.01}_{-0.01}$ | $0.529^{+0.030}_{-0.023}$ | $83.9^{+0.6}_{-0.7}$ | $8.50^{+0.15}_{-0.12}$ | $0.541^{+0.004}_{-0.005}$ | $0.63^{+0.04}_{-0.03}$ | -3395.1 |
|          | 5                               | $17.2^{+0.7}_{-0.6}$ | $0.18^{+0.01}_{-0.01}$ | $0.533^{+0.027}_{-0.022}$ | $82.8^{+0.6}_{-0.7}$ | $7.88^{+0.13}_{-0.12}$ | $0.535^{+0.004}_{-0.004}$ | $0.63^{+0.04}_{-0.04}$ | -3403.3 |
|          | 6                               | $18.0^{+0.7}_{-0.7}$ | $0.18^{+0.01}_{-0.01}$ | $0.536^{+0.027}_{-0.023}$ | $82.0^{+0.6}_{-0.7}$ | $7.53^{+0.13}_{-0.12}$ | $0.536^{+0.004}_{-0.004}$ | $0.62^{+0.04}_{-0.03}$ | -3425.1 |
| unbiased | 4                               | $23.5^{+0.8}_{-0.7}$ | $0.16^{+0.01}_{-0.01}$ | $0.523^{+0.026}_{-0.022}$ | $76.5^{+0.6}_{-0.8}$ | $7.89^{+0.16}_{-0.14}$ | $0.529^{+0.005}_{-0.006}$ | $0.72^{+0.06}_{-0.04}$ | -2229.2 |
|          | 5                               | $24.6^{+1.0}_{-0.6}$ | $0.15^{+0.01}_{-0.01}$ | $0.521^{+0.030}_{-0.021}$ | $75.5^{+0.6}_{-1.0}$ | $7.44^{+0.18}_{-0.13}$ | $0.527^{+0.005}_{-0.006}$ | $0.70^{+0.06}_{-0.04}$ | -2240.8 |
|          | 6                               | $25.2^{+0.9}_{-0.6}$ | $0.15^{+0.01}_{-0.01}$ | $0.521^{+0.027}_{-0.021}$ | $74.8^{+0.6}_{-0.9}$ | $7.24^{+0.16}_{-0.11}$ | $0.526^{+0.004}_{-0.006}$ | $0.69^{+0.06}_{-0.04}$ | -2249.2 |

**Table 2.**  $T_{90}$  distribution parameters.

| Sample   | Significance level ( $\sigma$ ) | $p_1$                | $T_{90c1}$<br>s        | $\sigma_1$                | $p_2$                | $T_{90c2}$<br>s         | $\sigma_2$                | $T_{90int}$<br>s       | $L$     |
|----------|---------------------------------|----------------------|------------------------|---------------------------|----------------------|-------------------------|---------------------------|------------------------|---------|
| full     | 4                               | $18.8^{+1.2}_{-1.0}$ | $0.65^{+0.08}_{-0.06}$ | $0.592^{+0.030}_{-0.025}$ | $81.2^{+1.0}_{-1.2}$ | $25.88^{+0.64}_{-0.54}$ | $0.507^{+0.005}_{-0.006}$ | $2.40^{+0.23}_{-0.19}$ | -3334.6 |
|          | 5                               | $18.8^{+0.6}_{-0.5}$ | $0.49^{+0.03}_{-0.03}$ | $0.553^{+0.017}_{-0.014}$ | $81.2^{+0.5}_{-0.6}$ | $21.56^{+0.29}_{-0.27}$ | $0.505^{+0.004}_{-0.004}$ | $1.95^{+0.10}_{-0.10}$ | -3344.0 |
|          | 6                               | $19.1^{+0.6}_{-0.6}$ | $0.44^{+0.02}_{-0.02}$ | $0.529^{+0.015}_{-0.013}$ | $80.9^{+0.6}_{-0.6}$ | $19.38^{+0.28}_{-0.26}$ | $0.515^{+0.004}_{-0.004}$ | $1.71^{+0.09}_{-0.09}$ | -3386.0 |
| unbiased | 4                               | $25.4^{+1.1}_{-1.0}$ | $0.53^{+0.05}_{-0.04}$ | $0.565^{+0.028}_{-0.021}$ | $74.6^{+1.0}_{-1.1}$ | $26.24^{+0.69}_{-0.62}$ | $0.494^{+0.007}_{-0.007}$ | $2.69^{+0.25}_{-0.22}$ | -2203.6 |
|          | 5                               | $25.2^{+0.7}_{-0.5}$ | $0.40^{+0.02}_{-0.02}$ | $0.529^{+0.017}_{-0.014}$ | $74.8^{+0.5}_{-0.7}$ | $22.28^{+0.39}_{-0.35}$ | $0.499^{+0.005}_{-0.005}$ | $2.13^{+0.13}_{-0.11}$ | -2214.9 |
|          | 6                               | $25.7^{+0.5}_{-0.5}$ | $0.36^{+0.01}_{-0.01}$ | $0.509^{+0.014}_{-0.012}$ | $74.3^{+0.5}_{-0.5}$ | $20.36^{+0.30}_{-0.28}$ | $0.505^{+0.004}_{-0.004}$ | $1.90^{+0.10}_{-0.09}$ | -2228.6 |



**Figure 3.**  $T_{50}$  (left) and  $T_{90}$  (right) distributions for the unbiased sample of 1841 GRBs. In each plot, the fit with two Gaussian components is shown with the thick solid curve; the components are shown with the dash-dotted curves. The vertical red lines denote the component centroids, the vertical blue line denotes the component intersection point  $T_{int}$ . Bottom panel of each plot shows the fit residuals.

### 3.2. Burst hardness

A more sophisticated classification of GRBs accounts for both the burst duration and its spectral hardness, see, e.g., [2, 11]. In this work, the spectral hardness ( $HR_{32}$ ) was calculated as the ratio of counts accumulated in the nominal G3 and G2 bands during the whole burst duration  $T_{100}$ .

**Table 3.** Results of  $\log \text{HR}_{32} - \log T_{50}$  distribution of 1611 events fits with two ( $L_2 = -1802.6$ ) and three ( $L_3 = -1759.5$ ) components.

| $N$ | $l$ | $a_x$                      | $T_{50c}$                 | $a_y$                      | $\text{HR}_{32c}$         | $\sigma_x$                | $\sigma_y$                | $r$                        | $p_l$                     |
|-----|-----|----------------------------|---------------------------|----------------------------|---------------------------|---------------------------|---------------------------|----------------------------|---------------------------|
| 2   | 1   | $-0.910^{+0.009}_{-0.009}$ | $0.123^{+0.003}_{-0.002}$ | $-0.086^{+0.008}_{-0.008}$ | $0.820^{+0.015}_{-0.014}$ | $0.457^{+0.018}_{-0.013}$ | $0.189^{+0.008}_{-0.007}$ | $0.071^{+0.030}_{-0.032}$  | $0.201^{+0.004}_{-0.003}$ |
|     | 2   | $0.809^{+0.007}_{-0.006}$  | $6.445^{+0.098}_{-0.096}$ | $-0.480^{+0.001}_{-0.001}$ | $0.331^{+0.001}_{-0.001}$ | $0.590^{+0.008}_{-0.008}$ | $0.221^{+0.002}_{-0.002}$ | $0.188^{+0.008}_{-0.009}$  | $0.799^{+0.003}_{-0.004}$ |
| 3   | 1   | $-0.874^{+0.023}_{-0.025}$ | $0.134^{+0.007}_{-0.008}$ | $-0.035^{+0.010}_{-0.014}$ | $0.924^{+0.020}_{-0.029}$ | $0.448^{+0.016}_{-0.014}$ | $0.145^{+0.010}_{-0.008}$ | $0.043^{+0.042}_{-0.042}$  | $0.163^{+0.015}_{-0.008}$ |
|     | 2   | $0.916^{+0.017}_{-0.010}$  | $8.236^{+0.322}_{-0.183}$ | $-0.447^{+0.007}_{-0.004}$ | $0.358^{+0.005}_{-0.003}$ | $0.506^{+0.006}_{-0.006}$ | $0.194^{+0.003}_{-0.004}$ | $0.023^{+0.016}_{-0.021}$  | $0.705^{+0.012}_{-0.026}$ |
|     | 3   | $-0.309^{+0.250}_{-0.105}$ | $0.491^{+0.381}_{-0.106}$ | $-0.609^{+0.033}_{-0.044}$ | $0.246^{+0.019}_{-0.024}$ | $0.716^{+0.038}_{-0.037}$ | $0.300^{+0.024}_{-0.039}$ | $-0.557^{+0.184}_{-0.069}$ | $0.133^{+0.016}_{-0.012}$ |

To account for the gain drift effect the rates expected in the nominal G2 and G3 energy bands (as given in section 2) were estimated using the best fit to the burst count spectrum with a power law with exponential cutoff function. We have found that fraction of relatively soft GRBs was higher in the beginning of the mission due to the softer boundaries of the trigger band (G2). To correct for this hardness bias we selected only GRBs detected after mid 1998 for further analysis. We also exclude the bursts with relative  $\text{HR}_{32}$  uncertainty greater than 0.5. The final list contains 1611 GRBs with  $S/N \geq 10$ .

We have fitted the  $\text{HR}_{32}$  distribution with a sum of log-normal components with the same method as was used for the durations and found that the distribution is best described with two components ( $-2(L_2 - L_3) \approx 6$ ).

### 3.3. Hardness-duration distribution

For the sample of 1611 GRBs described in the previous section, we have analyzed hardness-duration distribution  $\log \text{HR}_{32} - \log T_{50}$  ( $\log T_{90}$ ) with a method described in section 3.1 using the conditional probability density of each component in the form similar to [11]:

$$p(x, y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-r^2}} \times \exp \left[ -\frac{1}{2(1-r^2)} \left( \frac{(x-a_x)^2}{\sigma_x^2} + \frac{(y-a_y)^2}{\sigma_y^2} - \frac{C}{\sigma_x\sigma_y} \right) \right], \quad (2)$$

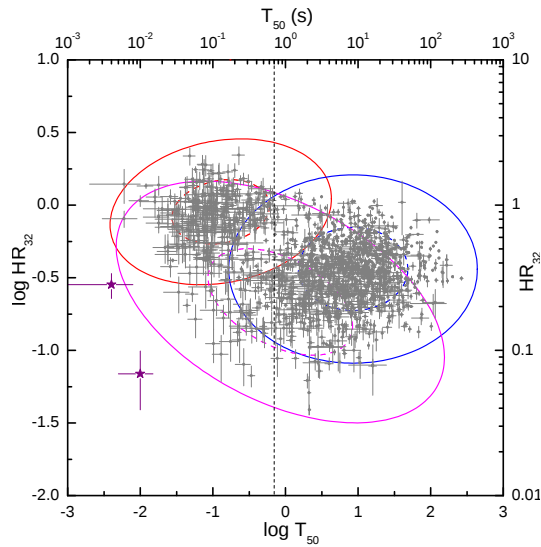
where  $x = \log T$  and  $y = \log \text{HR}_{32}$ ;  $a_x, a_y$  are the centroids;  $\sigma_x, \sigma_y$  are the dispersions;  $r$  is the correlation coefficient; and  $C = 2r(x-a_x)(y-a_y)$ .

The parameters of  $\log \text{HR}_{32} - \log T_{50}$  distribution fits by two and three components are presented in table 3. The three component fit is shown in figure 4. The likelihood ratio test strongly favors the three-component model, the observed  $-2(L_2 - L_3) \approx 86$  and 109 for distribution involving  $T_{50}$  and  $T_{90}$ , respectively, corresponds to a chance probability  $P < 10^{-16}$ . The fourth component further improves the fit, in particular  $-2(L_3 - L_4) \approx 29$  ( $P \sim 10^{-4}$ ) for the distribution involving  $T_{50}$  (the hardness- $T_{90}$  distribution shows a more complex shape, since even the univariate  $T_{90}$  distribution may be described by three components, see section 3.1).

The obtained three components correspond to well known short/hard and long/soft GRB populations, with two components corresponding to short/hard and long/soft GRBs; and the third, sparse component centered at soft GRBs with intermediate (0.1–10 s) durations. The fourth component partially covers the hardest and longest part of short GRB population. The parameters of the short/hard component do not change significantly between two- and three-component fits.

## 4. Summary and discussion

We presented the classification of Konus-*Wind* GRBs using burst durations and spectral hardness. We demonstrated that  $T_{50}$  distributions are well fitted with a mixture of two log-normal components, and estimated the fraction of short GRBs to be  $\sim 17\%$  ( $\sim 500$  events).



**Figure 4.**  $\log HR_{32}$ – $\log T_{50}$  distribution of 1611 KW GRBs, see text for details. The 68.27% and 99.73% contours of three Gaussian components are shown with dashed and solid lines, respectively. Vertical dashed line corresponds to the boundary  $T_{50} = 0.7$  s between long and short KW GRBs. The two bright short/soft events excluded from the fit are shown with stars: GRB 110616B ( $T_{50} \sim 4$  ms) and GRB 171108A ( $T_{50} \sim 10$  ms).

The asymmetry of the "long-duration" peak in the  $T_{90}$  distribution may result from the underestimation of burst durations at the right tail of the distribution.

In the hardness-duration plane the KW bursts fall into two well known populations: the short/hard and the long/soft ones. Both populations are well described by a single Gaussian component. In addition, the third component is needed to describe soft GRBs with intermediate (0.1–10 s) durations. Such a complex shape of the GRB population may be caused by a combination of time dilation and spectral softening that affect bursts arriving from a wide range of cosmological distances, see e.g. [8]. It was shown recently, that the triple-Gaussian fit is not necessarily the best solution for GRB hardness-duration distributions, it may be avoided by fitting them with only two skewed components [12]. The presence and the nature of the fourth GRB group needs further investigation.

GRB 110616B and GRB 171108A, see figure 4, are the shortest and the softest short bursts, respectively, among the entire sample of  $\sim 3000$  KW GRBs analyzed in this work, located at the outskirts of the "intermediate" GRB cluster. Further analysis involving burst energetics and spectrum is required to reveal the nature of these bursts.

The two-cluster decomposition presented previously in [7, 8] was derived using the smaller sample of KW bursts detected up to 1 January 2011, and its parameters are consistent with the two-component fit obtained in this work. The population of Type I GRBs (merger origin) detected by KW are well described by short/hard component, while Type II GRBs (core collapse origin) are consistent with superposition of two longer and softer components.

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