Integrated criteria of gamma-ray bursts spectral hardness

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Abstract. Most part of gamma-ray bursts (GRBs) spectra are well described by Band model with following parameters: \( \alpha \), \( \beta \) (spectral indices in low and high energy bands) and \( E_{\text{peak}} \) (energy of spectral peak). For several GRB parameter \( \beta \) characterizing the spectral shape in the region up to some hundred MeV (for example, GRB100724B). Moreover, Band spectrum of GRB080916C covering 6 orders of magnitude. Until recently spectral hardness parameter \( H_{32} \) (the ratio of total counts in the 100 - 300 keV and 50 - 100 keV energy range) was used for additional classification events on hard and soft, for GRBs groups selection on hardness and duration distributions (subgroup of intermediate bursts) and so on. However, \( H_{32} \) is defined in energy intervals 50-100 keV and 100-300 keV, but for some GRB \( E_{\text{peak}} > 300 \) keV and this value is outside regions of \( H_{32} \) definition. Thus, parameter \( H_{32} \) is incompletely represents spectral properties of such events. Basing on Band model we introduce new integral criteria could be used in the wide energy band for data analysis in past experiments such as BATSE (0.02 – 2 MeV), COMPTEL (0.8 – 30 MeV); EGRET (20 MeV – 30 GeV); in now operated experiments Fermi (8 keV – 1MeV, 200 keV – 40 MeV and 300 MeV – 300 GeV), AGILE (18 – 60 keV and 30 MeV – 50 GeV) and in future experiments: GAMMA-400 (0.1 – 3000 GeV) and so on. In the present work spectral parameters taken from BATSE and from Fermi catalogues were analyzed and the new integral criteria were investigated. Results of data studying have shown that new criteria allow making GRB classification including intermediate bursts subgroup separation.

1. Introduction
GRBs were first registered by Vela series satellites in the end of 1960 [1]. Since this time several tens of experiments on GRBs observations were made. The first detailed GRB catalogue was obtained as result of BATSE experiment onboard the Compton

Figure 1. GRBs duration distributions for BATSE catalogues (a) and Fermi/GBM spectral catalogue (b).
Gamma Ray Observatory (CGRO) [2]. Data analysis of this catalogue events have shown that several models described GRB spectra [3] – see table 1, but the most part of gamma-ray bursts (GRB) spectra are well described by Band model [4] with following parameters: \( \alpha, \beta \) (spectral indices in low and high energy bands) and \( E_{\text{peak}} \) (energy of spectral peak). Also spectral hardness parameter \( H_{32} \) (the ratio of total counts in the 100-300 keV and 50 - 100 keV energy range) was used for additional classification events on hard and soft [5], for GRBs groups selection on hardness and duration distributions (subgroup of intermediate bursts [6]) and so on. The duration distribution for BATSE GRBs from 4B current catalogue [7] and nontriggered bursts catalogue [8, 9] are presented at figure 1a. The data analysis have shown the existence of intermediate GRB subgroup more intensive than short and long events (such bursts were absent in catalogue of faint bursts separated by ground analysis and had intensity lower than one sufficient for onboard trigger.

### Table 1. GRB spectral models and their parameters

| Model | Model parameters |
|-------|------------------|
| **Band** model: \( f_{\text{Band}}(E) = \begin{cases} A(E/100\text{keV})^\alpha \exp(-E(2+\alpha)/E_{\text{peak}}) \\ \text{for } E < (\alpha-\beta)E_{\text{peak}}/(2+\alpha) \equiv E_{\text{break}} \\ A[(\alpha-\beta)E_{\text{peak}}/(100(2+\alpha))]^{(\alpha-\beta)} \exp(\beta-\alpha)(E/100)^\beta \\ \text{for } E \geq (\alpha-\beta)E_{\text{peak}}/(2+\alpha) \end{cases} \) | \( A: \) amplitude (ph/(s\times cm^2\times keV)), \( \alpha: \) low-energy spectral index, \( \beta: \) high-energy spectral index, \( vF_v: \) “peak” energy \( E_{\text{peak}} \) (keV). |
| **Comptonized spectrum (COMP) model:** | \( f_{\text{COMP}}(E) = A \left(E/E_{\text{piv}}\right)^\lambda \exp(-E(2+\lambda))/E_{\text{peak}} \) |
| **Broken power - law (PLAW) model:** | \( f_{\text{PLAW}}(E) = A \begin{cases} \left(E/E_{\text{piv}}\right)^\lambda, & E \leq E_b \\ \left(E_b/E_{\text{piv}}\right)^\lambda \left(E/E_b\right)^\lambda_b, & E > E_b \end{cases} \) |
| **Smoothly broken power - law (SBPL) model:** | \( f_{\text{SBPL}}(E) = A \left(E/E_{\text{piv}}\right)^b \right. \) |
| \( \beta = m\Delta \ln \left(\frac{e^a - e^{-a}}{2}\right), \beta_{\text{piv}} = m\Delta \ln \left(\frac{e^{\alpha_{\text{piv}}} - e^{-\alpha_{\text{piv}}}}{2}\right), m = \frac{\lambda_2 - \lambda_1}{2}, \) | \( \lambda_1: \) lower power-law index, \( E_b: \) break energy (keV), \( \Delta: \) break scale in decades of energy, \( \lambda_2: \) upper power-law index. |
| \( \alpha = \frac{\log_{10}(E/E_b)}{\Delta}, \alpha_{\text{piv}} = \frac{\log_{10}(E_{\text{piv}}/E_b)}{\Delta}, b = \frac{\lambda_2 + \lambda_1}{2} \) | |

#### 2. GRB spectral criteria

Now 5 satellite experiments observing GRB hard \( \gamma \)-emission up to several MeV: Fermi [9] (8 keV – 1 MeV, 200 keV – 40 MeV and 100 MeV – 300 GeV), AGILE [10] (18 – 60 keV and 30 MeV – 50 GeV), INTEGRAL [11] (3 – 35 keV, 15 keV – 1 MeV, 20 keV – 8 MeV), Suzaku [12] (0.4 – 10 keV, 10 – 600 keV, 50 keV – 5 MeV), and Wind [13] (10 – 800 keV, 15 keV – 10 MeV). In the present time GRB observed in the very wide energy range, for example Band spectrum of GRB080916C covering 6 orders of magnitude [14]. For several GRB parameter \( \beta \) characterizing the spectral shape in the region up to some hundred
The distribution of GRBs with Band spectra from BATSE spectral catalogue on $I_1$ criterion (a) and combination of $I_1$ and $I_2 H = I_1 / \lg I_2$ (b). Circles presented values of criteria, histograms shown GRBs duration distributions: dotted line represented whole events subsets and thin one shown subset of bursts with Band spectra.

MeV (for instance, GRB100724B [15]). However, $H_{32}$ is defined in energy intervals $50 – 100$ keV and $100 – 300$ keV, but for some GRB $E_{\text{peak}} > 300$ keV and this value is outside regions of $H_{32}$ definition. Thus, parameter $H_{32}$ is incompletely represents spectral properties of such events.

Based on the Band model we introduce two integral spectrum characteristics constrained using model parameters:

$$I_1 = A \int_{E_{\text{min}}}^{E_{\text{peak}}} \left( \frac{E}{100 \text{keV}} \right)^{\alpha} \exp \left( -\frac{E (2 + \alpha)}{E_{\text{peak}}} \right) dE = \frac{A}{100^\alpha \text{keV}} \left( \frac{E_{\text{peak}}}{2 + \alpha} \right)^{\alpha + 1} \left[ \Gamma \left( \alpha + 1, \frac{(2 + \alpha) E_{\text{min}}}{E_{\text{peak}}} \right) - \Gamma \left( \alpha + 1, \frac{(2 + \alpha) E_{\text{max}}}{E_{\text{peak}}} \right) \right],$$

$$I_2 = A \int_{E_{\text{peak}}}^{E_{\text{max}}} \frac{E_{\text{max}}}{100 \text{keV}} \left( \frac{(\alpha - \beta) E}{2 + \alpha} \right)^{(\alpha - \beta)} \exp \left( \beta - \alpha \right) \left( \frac{E}{100 \text{keV}} \right)^{\beta} dE = \frac{A}{100^\alpha \text{keV}} \left( \frac{E_{\text{peak}}}{2 + \alpha} \right)^{\alpha + 1} \left[ \Gamma \left( \frac{1}{\beta}, \frac{(\beta - \alpha) E_{\text{peak}}}{100 \text{keV}} \right) - \Gamma \left( \frac{1}{\beta}, \frac{(\beta - \alpha) E_{\text{max}}}{100 \text{keV}} \right) \right],$$

were $\Gamma$ - gamma - function.

The analysis of BATSE spectral catalogue for GRBs with Band spectra [16] have shown several features on the GRBs distributions on $I_1$ and $I_2$ criteria and their combination $H = I_1 / \lg I_2$ located at $t_{90} \sim 12$ s – see figure 2. These features could be associated with intermediate GRB subgroup presence.

Than we have constructed the similar criteria for Fermi catalogue events [17] separately for GRBs with different spectral models (see figure 3). The investigation of Fermi GRB distribution on the presented criteria allows separating areas corresponding subgroup of intermediate GRB. It is seen that bursts with from intermediate subgroup are mostly absent in subset which spectral characteristics described by SBPL model. The summarized data of intermediate GRB from different spectral subsets are presented at the figure 1b.

The mean values of intermediate bursts duration $t_{90}$ are in the time interval 3-4 s and similar for events from BATSE and Fermi catalogues.
3. Conclusion

In the present work spectral parameters taken from BATSE and Fermi catalogues were analyzed and the new integral criteria were introduced. The detailed data analysis has shown that there are some features at the GRB distributions on these criteria and duration could be associated with intermediate bursts subgroup both for BATSE and Fermi catalogues events. Intermediate bursts duration $t_{90}$ mean values are in the time interval 3-4 s both for bursts from BATSE and Fermi catalogues. These results allow concluding that presented criteria could be used to making GRB classification including intermediate bursts subgroup.
separation. We used only spectral approximations for obtaining the values of criteria $I_1$ and $I_2$ allows to study data in the wide energy band and analyze events from databases of different experiments: past ones such as BATSE (0.02 – 2 MeV), COMPTEL (0.8 – 30 MeV); EGRET (20 MeV – 30 GeV) [1] and so on, now operated ones (for example, Fermi [9] (8 keV – 1MeV, 200 keV – 40 MeV and 300 MeV – 300 GeV), AGILE [10] (18 – 60 keV and 30 MeV – 50 GeV), etc) and future instruments.

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