Distributions of the Hardness Ratio of short and Long Gamma-Ray Bursts in Different Time Intervals within the First 2 Seconds

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ABSTRACT

In the present paper, we investigated the distribution of hardness ratio (HR) for short and long gamma-ray bursts (GRBs) in different time scales for the first two seconds. After including and subtracting the background count, we performed a Kolmogorov–Smirnov (K-S) test to the HR distributions of the two classes of GRBs in each time interval. We obtained from our analysis, the HR distributions of the two classes of bursts are obviously different. The result indicates that the two kinds of bursts probably originate from the different mechanisms or have different central engines. In addition, we found that the hardness ratio of short bursts within the time interval of 0–0.96 seconds changes hard-to-soft, on the other hand long bursts do not. The two kinds of bursts have different characteristics in the first 2 seconds which might be associated with different physical mechanisms.

Key words: gamma rays: bursts– methods: statistical

1 INTRODUCTION

Based on the bimodal time interval distribution, gamma–ray bursts (GRBs) can be divided into two subclasses with T90=2s, first one is the short burst with a mean T90 $\sim$ 0.3s and observed event rate is $\sim$ 1/3 of the long bursts and the second one is long burst class with T90 $\sim$ 20s (Kouveliotou...
et al. 1993; Norris et al. 2000). Statistical studies revealed that these two classes have different distributions of the hardness ratio (short bursts being harder), pulse width, separation time scale, number of pulses per bursts, different anti–correlations between the spectral hardness and duration. It suggests that the two classes might be intrinsically different (Qin et al. 2000, 2001; hurley et al. 1992; Kouveliotou et al. 1993; fishman & meegan 1995, Norris et al. 2000; Nakar & Piran 2002). A generally accepted scenario is that short bursts are likely to be produced by the merger of compact objects while the core collapse of massive stars is likely to give rise to long bursts (see, e.g., Zhang & Mésazáros, 2003; Piran, 2004).

However, there are some evidences indicating that the two classes might be originated from the same physical process. Schmidt (2001) suggested that both short and long bursts have a similar luminosity. Lamb et al. (2002) found that $< V/V_{\text{max}} >$, the angular distribution, the energy dependence of the duration and the hard–to–soft spectral evolution of short bursts are similar to those of long bursts. Recently, Ghirlanda, Ghisellini & Celotti (2004) have shown that the emission properties of short bursts are similar to that of the first 2 seconds for long events and concluded that the central engine of long and short bursts is the same, only working for a longer time for long GRBs. Based on this work, Yamazaki, Ioka & Nakamura (2004) proposed a unified model of short and long GRBs and suggested that the jet of GRB consists of multiple subjets or subshells, where the multiplicity of the subjets along the line of sight $n_s$ is an important parameter. They showed that if $n_s$ is large ($\gg 1$), the event looks like a long GRB, while if $n_s$ is small ($\sim 1$), the event looks like a short GRB.

Thus, it is still unclear whether the short and the long bursts are intrinsically the same. To find the mechanism of the central engine of GRBs, it is necessary to solve this question with focused effort. Based on the analysis of Ghirlanda et al. (2004), it is expected that the first 2 second behavior of short and long bursts would be the same. If so, the hardness ratio distributions of the two classes should share the same character within this period. This will be checked in the following.

Distributions of the hardness ratio of short and long GRBs for each 64 ms time interval within the first 2 seconds of bursts are presented in section 2. In section 3 we present the results of the K-S test to the distributions of the two kinds of bursts, where some typical statistical values of the distributions are also provided. A brief discussion is presented in section 4.
2 DISTRIBUTIONS OF THE HARDNESS RATIO OF SHORT AND LONG GRBS WITHIN THE FIRST 2 SECONDS

There are 2041 GRBs with T90, including 500 short GRBs and 1541 long GRBs, available in the current BATSE burst catalog. In this catalogue observations made during April 21, 1991 to May 26, 2000 by BATSE with 64 ms temporal resolution and four-channel spectral resolution were presented. We found that this catalogue has 462 short bursts and 1428 long bursts.

In this paper we mainly focused our attention on the question, whether the two classes have the same hardness ratio distribution within the first 2 seconds? The hardness ratio is defined as

\[ HR_n \equiv \frac{\text{count}_3}{\text{count}_2}, \]

where \( \text{count}_2 \) and \( \text{count}_3 \) are the counts of the second channel and the third channel within the 64 ms time interval respectively, \( n \) represents the \( n \)th 64 ms time interval after the trigger time. We considered two different situations, the hardness ratio is calculated with the original data which contain the background counts (case 1), and the hardness ratio is calculated when the background counts are subtracted (case 2).

In case 1, we have two ways for calculating the hardness ratio for short bursts: one is to calculate the hardness ratio for any of the 64 ms interval from the trigger time to the end of T90 (in this way some sources will be missed within the time interval between the end of T90 and the end of the first 2 seconds due to their short durations); the other way is to calculate the ratio for all 64 ms intervals within the first 2 seconds of bursts (in this way, no sources will be missed in any interval within the first 2 seconds). For long bursts, as their duration is larger than 2 seconds, we adopted the second approach applied for the short bursts. We therefore, obtained three distributions of the hardness ratio for any of the 64 ms interval concerned which we call distributions 1, 2 and 3, respectively.

In case 2, for each source, we assumed its signal data covers the range of \( t_{\text{min}} \leq t \leq t_{\text{max}} \), where \( t_{\text{max}} - t_{\text{min}} = 2T_{90} \), and \( t_{\text{min}} \) is at \( T_{90}/2 \) previous to the start of \( T_{90} \). If \( t_{\text{min}} \) is previous to the start of the data, we then assigned \( t_{\text{min}} \) to be the start of trigger time. Data beyond this range will be taken to find the fit for the background, which will be fitted with a liner function. This background fit will then be applied to the signal interval and be taken as the background count rate there. We used the data in the first 2 seconds which subtract the corresponding background counts to calculate the corresponding hardness ratio. For short bursts, we calculated the hardness ratio from the trigger time to the end of T90 and obtained the corresponding distribution (distribution 4). For long bursts we calculated the hardness ratio in the first 2s and got the corresponding distribution (distribution 5).
The three distributions of case 1 are presented in Fig. 1 and the two distributions of case 2 are presented in Fig. 2. There are 27 plots in total for each of the two figures, which represent intervals 0–0.064 s ($h_1$), 0.064–0.128 s ($h_2$), ..., and 1.664–1.728 s ($h_{27}$), respectively. As the number of the hardness ratio data after the 1.728 s is very small for short bursts, only 27 plots are presented.

### Table 1. Probability of the K-S test to the hardness ratio distributions of the two classes of GRBs

| intervals | probability 1 | probability 2 | probability 3 | median 1 | median 2 | median 3 | median 4 | median 5 |
|-----------|---------------|---------------|---------------|----------|----------|----------|----------|--------|
| 1         | 0.1938E-29    | 0.1938E-29    | 0.0000E+00    | 1.094    | 0.912    | 1.503    | 0.945    |
| 2         | 0.3832E-17    | 0.6548E-12    | 0.0000E+00    | 1.107    | 0.929    | 1.565    | 0.949    |
| 3         | 0.6243E-07    | 0.3559E-37    | 0.5517E-31    | 1.018    | 0.934    | 1.435    | 0.959    |
| 4         | 0.2438E-02    | 0.8775E-01    | 0.912         | 0.924    | 0.936    | 1.477    | 0.962    |
| 5         | 0.9181E-03    | 0.3965E-23    | 0.904         | 0.908    | 0.923    | 1.327    | 0.950    |
| 6         | 0.2084E+00    | 0.3041E-16    | 0.887         | 0.926    | 1.142    | 0.953    |
| 7         | 0.7741E-01    | 0.2415E-15    | 0.885         | 0.920    | 1.248    | 0.945    |
| 8         | 0.8181E-01    | 0.9417E-13    | 0.878         | 0.922    | 1.163    | 0.948    |
| 9         | 0.3096E+00    | 0.2510E-09    | 0.884         | 0.930    | 1.015    | 0.960    |
| 10        | 0.6099E+00    | 0.3260E-12    | 0.873         | 0.919    | 0.814    | 0.948    |
| 11        | 0.8810E+00    | 0.6947E-08    | 0.870         | 0.926    | 0.977    | 0.954    |
| 12        | 0.8999E+00    | 0.2112E-06    | 0.867         | 0.909    | 0.955    | 0.938    |
| 13        | 0.5467E+00    | 0.1775E-06    | 0.867         | 0.916    | 0.800    | 0.944    |
| 14        | 0.2414E+00    | 0.8912E-09    | 0.869         | 0.924    | 0.733    | 0.957    |
| 15        | 0.9558E-01    | 0.1985E-10    | 0.862         | 0.921    | 0.543    | 0.956    |
| 16        | 0.7092E+00    | 0.1015E-07    | 0.853         | 0.918    | 0.615    | 0.945    |
| 17        | 0.3297E-01    | 0.3483E-06    | 0.865         | 0.916    | 1.653    | 0.948    |
| 18        | 0.1441E+00    | 0.3488E-06    | 0.862         | 0.916    | 1.631    | 0.949    |
| 19        | 0.6253E-01    | 0.1631E-04    | 0.864         | 0.910    | 1.520    | 0.951    |
| 20        | 0.4470E+00    | 0.1564E-02    | 0.862         | 0.910    | 0.820    | 0.936    |
| 21        | 0.1915E+00    | 0.1496E-01    | 0.866         | 0.902    | 0.877    | 0.936    |
| 22        | 0.3636E+00    | 0.9226E-02    | 0.870         | 0.917    | 0.872    | 0.946    |
| 23        | 0.7136E+00    | 0.3459E-03    | 0.872         | 0.898    | 0.561    | 0.931    |
| 24        | 0.4024E+00    | 0.3804E+00    | 0.860         | 0.908    | 0.981    | 0.937    |
| 25        | 0.3405E-01    | 0.1515E-01    | 0.857         | 0.895    | 1.003    | 0.926    |
| 26        | 0.4801E-01    | 0.2888E+00    | 0.871         | 0.890    | 0.978    | 0.921    |
| 27        | 0.3061E-01    | 0.6111E-02    | 0.862         | 0.900    | 0.550    | 0.930    |

3 THE K-S TEST TO AND THE MEDIAN VALUE OF THE HARDNESS RATIO DISTRIBUTIONS

In order to check if the behavior of the two classes of GRBs are the same within the first 2 seconds, we performed a K-S test to the hardness ratio distributions mentioned above. The results are listed in Table 1, where median values of the distributions are also presented. As shown in the table, probability 1 represents the probability associated with the K-S test to the distributions 1 and 3, probability 2 denotes the probability obtained from the K-S test to the distributions 2 and 3, while probability 3 describes the probability produced by the K-S test to the distributions 4 and 5. We have also reported in the table, median 1, 2, 3, 4, and 5 which are the median values of the distributions 1, 2, 3, 4, and 5, respectively.

From Table 1 and Fig. 3, we find that probabilities associated with the K-S test to distributions...
Distributions of the Hardness Ratio of short and Long Gamma-Ray Bursts in Different Time Intervals within the First 2 Seconds

1 and 3 vary significantly. In the first five time intervals, the probability is very small (it is very close to zero), indicating that during this period the hardness ratio distributions of the two classes of GRBs are unlikely to arise from a same parent population. From the 8th time interval to the 12th time interval, the probability rises monotonously and reaches its maximum $\sim 0.9$. Within the 12th and 15th time intervals, it drops monotonously and reaches its rock bottom at the 15th time interval. After the 15th time interval, the probability curve seems to arise from fluctuation which we believe to be due to the relatively small number of short bursts (in fact, after the 15th time interval, the number of short bursts is $\sim 33$ which is much smaller than that of long bursts). The probability of the K-S test associated with distributions 2 and 3 is significantly small ($\sim 0$) which indicates that in this case the hardness ratio distributions of the two GRB classes are unlikely to arise from the same parent population. Note that, after T90, the hardness ratio distribution of short bursts reflects the background count ratio rather than the signal count ratio. It is, therefore, reasonable that the probability associated with distributions 2 and 3 is $\sim 0$. For distributions 4 and 5, for which the background count has been subtracted, the probability of the K-S test is very small (see Table 1 and Fig. 3), which suggest that the hardness ratio distributions of the two classes of the GRBs are unlikely to arise from the same parent population and therefore they are likely to originate from different physical processes.

For distributions 1 and 3, in the 11th and 12th time intervals the probability of the K-S test is very large (close to 1). Can we draw a conclusion that the two classes originated from a same physical process in these time intervals? The answer is no. If short and long GRBs originate from a same physical process and have a same central engine as suggested in some previous works (see, e.g., Ghirlanda et al. 2004; Yamazaki et al. 2004), they should have the same hardness ratio distributions within the first 2 seconds. But the fact is that, in the first 5 time intervals the K-S probability is almost $\sim 0$ and it is $\sim 1$ only in the 11th and 12th time intervals, which is in confliction with the scenario that short and long GRBs originate from the same physical process. Note that a character of the development of the GRB spectrum is hard-to-soft. Since the hardness ratio of short bursts varies enormously, it is expected that within some time interval, the hardness ratio of short bursts can become the same as that of long bursts, and this we believe to be the reason why the possibility of the K-S test of the two hardness ratio distributions in the 11th and 12th time intervals is as large as $\sim 1$. This is supported by the median value of the hardness ratio distributions shown in fig. 5, where the median values of short and long bursts from the 8th to 12th time intervals are almost the same.

However, for distributions 4 and 5 for which the background count is subtracted, the probability
of the K-S test in all the 64 ms time intervals concerned is almost 0. If the method of subtracting the background count is reasonable, we can take the data subtracting the background count as the true signal data of the bursts. In this situation, it would be natural to conclude from the analysis that the two GRB classes are unlikely to be intrinsically the same. This can be convinced when one makes a sum of counts of the signal data within the first 2 seconds and calculates the corresponding hardness ratios and then performs a K-S test to the hardness ratio distributions of the two classes of bursts, as is shown in the following.

In addition, besides making a sum of counts within the first 2 seconds for long bursts, we also calculate the sum of counts ranging from the trigger time to the end of T90 for short bursts, in both the cases of including and subtracting the background counts. We then calculate the corresponding hardness ratios. The hardness ratio distributions of short and long bursts in the two cases are presented in Fig. 4. The probabilities of the K-S test to the hardness ratio distributions of short and long bursts in the two cases are $1.1153706 \times 10^{-13}$ (including the background count) and $2.4111853 \times 10^{-27}$ (subtracting the background count), respectively. They are so small that the two kinds of bursts are unlikely to be associated with the same physical process and to have a same central engine.

In Fig. 5 we have shown all the median values of distributions 1, 2, 3, 4, and 5. We find that for long bursts, the median values do not show a fluctuation and keep almost the same. For short bursts, within the period before the 15th, 64 ms time interval (the range of 0–0.96s), distributions 1, 2, and 4 show a same trend: monotonously dropping. After this time interval, the median of distribution 4 exhibits an obvious character of fluctuation, while for distribution 1 the character is insignificant. Meanwhile, the median of distribution 2 keeps to be the same. One can conclude from this analysis that short and long bursts are intrinsically different: the hardness ratio of long bursts does not obviously develop with time, while that of short bursts evolves significantly and it becomes much softer when time goes on. In addition, we find that, during the beginning phase of bursts, the hardness ratio of short GRBs is larger than that of long ones, which is accordant with the result that short bursts are typically harder (Dezalay et al. 1996).

4 DISCUSSION AND CONCLUSIONS

Distributions of the hardness ratio in different 64 ms time intervals within the first 2 seconds for short and long bursts are studied in the cases of including (case 1) and subtracting (case 2) the background count. The main aim of this work is to find in the first two seconds whether the hardness ratio of short and long bursts evolves and the two classes of GRBs arise from a same
Distributions of the Hardness Ratio of short and Long Gamma-Ray Bursts in Different Time Intervals within the First 2 Seconds

physical process and have a same central engine. From Figs. 1 and 2, no significant evolution of the hardness ratio can be detected. In order to find an evolutionary clue, we investigated the median value of these distributions, as shown in Fig. 5. From Fig. 5 we found that the median value of short bursts monotonously drops with time from 0 to 0.96s, and that of long bursts does not show a significant evolution. This implies that for short bursts their spectra evolve significantly with a character of hard-to-soft within the first 2 seconds while for long bursts their spectra do not show an obvious change during this period.

A K-S test to hardness ratio distributions of short and long bursts in both cases of including and subtracting the background count for the same 64ms time intervals shows that for the majority of the time intervals concerned the probability is very small (close to zero). This indicates that in these time intervals the mechanisms of the two types of bursts are unlikely to be intrinsically the same. Making a sum of counts over the whole first 2 seconds and performing a K-S test to the corresponding hardness ratio distributions we can also reach the same conclusion. Our analysis suggests that short and long GRBs probably originate from different physical processes or have different central engines and they are intrinsically different and distinct subclasses.

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Figure 1. Distributions of the hardness ratio associated with time for short and long bursts in case 1. Dashed lines represent long bursts (distributions 3), solid lines represent short bursts calculated within the first 2 seconds (distributions 2), and dotted lines stand for short bursts calculated within T90 (distributions 1), respectively.
Distributions of the Hardness Ratio of short and Long Gamma-Ray Bursts in Different Time Intervals within the First 2 Seconds.

Figure 2. Distributions of the hardness ratio associated with time for short and long bursts in case 2. Dashed lines represent long bursts (distributions 5), and solid lines denote short bursts (distributions 4), respectively.
Figure 3. Probability of the K-S test associated with different 64 ms time intervals within the first 2 seconds. Filled circles represent the probability obtained from the K-S test to distributions 1 and 3, and open squares stand for the probability associated with the K-S test to distributions 2 and 3, and open circles denote the probability produced by the K-S test to distributions 4 and 5, respectively.

Figure 4. Distributions of the hardness ratio within the first two seconds for short and long bursts in cases 1 (denoted a) and 2 (denoted b), where solid lines represent the distribution of long bursts and dashed lines stand for that of short bursts.
Figure 5. Median of distributions 1, 2, 3, 4 and 5 in different 64 ms intervals within the first 2 seconds. The filled circle, open circle, open square, open square plus cross, and open circle plus cross represent distributions 1, 2, 3, 4 and 5, respectively.