Correlations between various hardness ratios of gamma-ray bursts

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ABSTRACT

We study correlations between various hardness ratios of gamma-ray bursts (GRBs) and investigate if there are any differences between the two classes of the objects in the distributions of the ratios. The study shows that: (1) almost all hardness ratios of GRBs are mutually correlated; (2) the most obvious correlation for both the short and long duration classes is that between $\log HR_{41}$ and $\log HR_{42}$, where HR_{ij} is the fluence in channel i divided by the fluence in channel j; (3) for the short duration class, $\log HR_{21}$ and $\log HR_{32}$ as well as $\log HR_{31}$ and $\log HR_{43}$ are not correlated, while for the long duration class, $\log HR_{21}$ and $\log HR_{42}$ as well as $\log HR_{21}$ and $\log HR_{43}$ are not correlated; (4) those most significant correlations for the long duration class are more obvious than that for the short duration class; (5) the data of hardness ratios for the long duration class are more concentrated, while that for the short duration class are more scattered; (6) the sources of the two classes are distributed in different areas in the hardness ratio—hardness ratio plot. These results suggest that, statistically, the slope of the higher part of the spectrum of the long duration bursts has nothing to do with that of the lower part; emissions at higher energy bands from the bursts of both short and long duration classes must be significantly different for different sources, while radiations at lower energy bands of the objects are relatively similar; the spectrum of the short duration bursts must be harder than that of the long duration bursts, confirming what the well-known hardness-duration correlation reveals; the profiles of the spectra between the long duration bursts must be more similar than that between the short duration bursts. The long duration bursts would share more common properties than the short duration bursts. A possible interpretation is proposed with the concept of the Doppler boosting in the relativistic beaming model in AGNs.

Key words: cosmology: observations — gamma rays: bursts — gamma rays: theory — methods: statistical

1 INTRODUCTION

Gamma-ray bursts (GRBs) are a transient astrophysical phenomenon in which the emission is confined exclusively to high energies: they are detected at gamma-ray bands and last shortly (from a few milliseconds to several hundred seconds). Since the discovery of the events about thirty years ago (Klebesadel et al. 1973), more and more data have been obtained (e.g., Fishman et al. 1994; Meegan et al. 1994, 1996, 1998; Paciesas et al. 1997, 1999). Based on the data available so far, statistical studies have recently unveiled many basic properties of the objects. For example, two separate classes of GRBs with a division at the duration of 2 s were detected (Dezalay et al. 1992; Hurley 1992; Kouveliotou et al. 1993); a correlation between the peak spectral hardness and the peak intensity was discovered (Atteia et al. 1991, 1994, 1997; Belli 1992; Mitrofanov et al. 1992, 1996; Paciesas et al 1992; Nemiroff et al. 1994; Mallozzi et al. 1995; Dezalay et al. 1997).

More recently, the hardness-duration correlation was confirmed by Fishman (1999) with a large number of bursts observed with BATSE. Generally, the hardness ratio is defined as the fluence in channel 3 ($\sim$ 100 to $\sim$ 300 keV) divided by the fluence in channel 2 ($\sim$ 50 to $\sim$ 100 keV) (see, e.g., Fishman et al. 1994). This quantity is more likely to present an intrinsic property of the objects rather than an observational one. It is noticed that, besides the two channel fluences, there are two other channel fluences available in the BATSE burst catalogs, e.g., channels 1 ($\sim$ 20 to $\sim$ 50 keV) and 4 ($>$ 300 keV) (see, e.g., Paciesas et al. 1997). Therefore, one can define more than one hardness ratios. We wonder if there are any meaningful statistical relations between these different hardness ratios. We also want to make clear if there are any differences between the two classes of the objects in the distributions of the ratios.

In Section 2, correlations between various hardness ratios of GRBs will be studied, while in Section 3, differences between the two classes of the objects in the distributions of the ratios will be investigated.

2 CORRELATIONS BETWEEN HARDNESS RATIOS

In the 4B catalog (Paciesas et al. 1997), there are 1027 sources with all of their four channel (1-4) fluences available. We then get a rather sizable sample from the catalog (called Sample 1). A hardness ratio HR_{ij} is defined as

$$HR_{ij} \equiv f_i/f_j, \tag{1}$$

where i and j denote the channels i and j respectively, and f_i and f_j represent the fluences of the corresponding channels respectively.

The plots of $\log HR_{ij} - \log HR_{i'j'}$ for Sample 1 are shown in Figures 1.1 to 1.15. The correlation coefficients for every couple of hardness ratios are presented in Table 1.

Table 1. Correlation coefficients for Sample 1 (N=1027)

	$\log HR_{31}$	$\log HR_{32}$	$\log HR_{41}$	$\log HR_{42}$	$\log HR_{43}$
$\log HR_{21}$	0.746	0.276	0.373	0.080	-0.037
$\log HR_{31}$		0.846	0.677	0.488	0.186
$\log HR_{32}$			0.678	0.640	0.298
$\log HR_{41}$				0.955	0.849
$\log HR_{42}$					0.924

From Table 1 and Figures 1.1 to 1.15 we find that almost all hardness ratios are mutually correlated, with only $\log HR_{21}$ and $\log HR_{43}$ being uncorrelated. The most obvious correlation is that between $\log HR_{41}$ and $\log HR_{42}$. It suggests that, statistically, the slope of the higher part of the spectrum of most GRBs has nothing to do with that of the lower part; emissions at higher energy bands from the objects must be significantly different for different sources, while radiations at lower energy bands must be relatively similar.

3 DIFFERENCES BETWEEN THE TWO CLASSES

To study the differences between the two classes of GRBs in the distributions of hardness ratios, we simply concern those sources with their data of the duration as well as the four channel fluences available. The bursts are divided into two classes with a division at the duration of 2 s: those sources with $T_{90} \leq 2$ s belong to the short duration class and those with $T_{90} > 2$ s constitute the long duration class, where T_{90} is the time during which the burst integrated counts increases from 5% to 95% of the total counts. We find 249 short duration sources (called Sample 2) and 706 long duration bursts (called Sample 3) from the 4B catalog.

The plots of $\log HR_{ij} - \log HR_{i'j'}$ for Samples 2 and 3 are shown in Figures 2.1 to 2.15. The correlation coefficients for every couple of hardness ratios for the samples are presented in Tables 2 and 3.

Table 2. Correlation coefficients for Sample 2 (N=249)

	$\log HR_{31}$	$\log HR_{32}$	$\log HR_{41}$	$\log HR_{42}$	$\log HR_{43}$
$\log HR_{21}$	0.653	-0.050	0.206	-0.218	-0.235
$\log HR_{31}$		0.724	0.558	0.280	-0.068
$\log HR_{32}$			0.549	0.568	0.125
$\log HR_{41}$				0.910	0.790
$\log HR_{42}$					0.887

Table 3. Correlation coefficients for Sample 3 (N=706)

	$\log HR_{31}$	$\log HR_{32}$	$\log HR_{41}$	$\log HR_{42}$	$\log HR_{43}$
$\log HR_{21}$	0.757	0.308	0.324	0.059	-0.060
$\log HR_{31}$		0.855	0.606	0.425	0.142
$\log HR_{32}$			0.624	0.572	0.254
$\log HR_{41}$				0.964	0.874
$\log HR_{42}$					0.939

From Tables 2 and 3 we find that, the two classes have similar correlations between hardness ratios: many of them are mutually correlated, with only a few exceptions. For the short duration class, $\log HR_{21}$ and $\log HR_{32}$ as well as $\log HR_{31}$ and $\log HR_{43}$ are not correlated, while for the long duration class, $\log HR_{21}$ and $\log HR_{42}$ as well as $\log HR_{21}$ and $\log HR_{43}$ are not correlated, suggesting that, statistically, the slope of the higher part of the spectrum of the long duration bursts has nothing to do with that of the lower part. The most obvious correlation for both the short and long duration classes is that between $\log HR_{41}$ and $\log HR_{42}$, showing that, statistically, emissions at higher energy bands from the bursts of both long and short duration classes must be significantly different for different sources, while radiations at lower energy bands must be relatively similar.

For the most obvious correlations shown in the two tables, those for the long duration class are more significant than that for the short duration class. One can find from Figures 2.1 to 2.15 that the data of hardness ratios for the long duration class are more concentrated, while that for the short duration class are more scattered. This may be the most significant difference between the two classes shown in the figures. It implies statistically that the profiles of the spectra between the long duration bursts must be more similar than that between the short duration bursts. The long duration bursts must share more common properties than the short duration bursts.

Figures 2.1 to 2.15 also show different distributions of the two classes. The short duration bursts tend to occupy the right top part of the figures, showing that, in general, their spectra must be harder than that of the long duration bursts, confirming what the well-known hardness-duration correlation reveals (see, e.g., Fishman 1999). This can be verified by a direct calculation for the two classes. For example, the mean value of $\log HR_{41}$ for Sample 2 is 1.5 while that for Sample 3 is 0.67.

4 DISCUSSION AND CONCLUSIONS

In the last two sections, we study the correlations between various hardness ratios of GRBs and investigate if there are any differences between the two classes of the objects in the distributions of the ratios with the data of the 4B catalog. The results are: (1) almost all hardness ratios of GRBs are mutually correlated; (2) the most obvious correlation for both the short and long duration classes is that between $\log HR_{41}$ and $\log HR_{42}$; (3) for the short duration class, $\log HR_{21}$ and $\log HR_{32}$ as well as $\log HR_{31}$ and $\log HR_{43}$ are not correlated, while for the long duration class, $\log HR_{21}$ and $\log HR_{42}$ as well as $\log HR_{21}$ and $\log HR_{43}$ are not correlated; (4) those most significant correlations for the long duration class are more obvious than that for the short duration class; (5) the data of hardness ratios for the long duration class are more concentrated, while that for the short duration class are more scattered; (6) the sources of the two classes are distributed in different areas in the $\log HR_{ij} - \log HR_{i'j'}$ plot. These results suggest that, statistically, the slope of the higher part of the spectrum of the long duration bursts has nothing to do with that of the lower part; emissions at higher energy bands from the bursts of both short and long duration classes must be significantly different for different sources, while radiations at lower energy bands must be relatively similar; the spectrum of the short duration bursts must be harder than that of the long duration bursts, confirming what the well-known hardness-duration correlation reveals; the profiles of the spectra between the long duration bursts must be more similar than that between the short duration bursts. The long duration bursts must share more common properties than the short duration bursts.

According to the most successful model proposed so far, GRBs would result in relativistically expanding fireballs, and the gamma-ray emission would arise after the fireball becomes optically thin, in shocks occurring either because the ejecta run into an external medium or because internal shocks occur in a relativistic wind (see Mészáros & Rees 1997). Several of the features reported in the first GRB detected over timescales of greater than days at X-ray and optical wavelengths, i.e., GB 970228 (Costa et al. 1997), agreed well with the theoretical expectations of the model. In the well-known relativistic beaming model used in AGNs (Rees 1966, 1967), the enhancement of the observed flux for a relativistically moving component is δ^p, with $p = 3 + \alpha$ in the case of a moving sphere and $p = 2 + \alpha$ in the case of a continuous jet, where δ is the Doppler factor and α is the spectral index of the component (see, e.g., Ghisellini et al. 1993). Recently, the correlation between polarization and variation for BL Lac objects was found able to be adopted to GRBs and a value as big as 100 of the Doppler factor for the bursts was estimated by the relation (see Fan et al. 1997, 1999; Cheng et al. 1999). As mentioned above, different to that radiated at lower energy bands, emissions of GRBs at higher energy bands are significantly different for different sources. This leads to the prospect that the Doppler boosting for GRBs might play a more important role at higher energy bands than at lower bands. If it is true, higher energies must be emitted by the fastest moving ejecta while lower energies be radiated by the slower moving components in both the isotropic expanding fireball model or the beaming model; or, the range of the spectral index of GRBs at higher energy bands must be significantly wider than that at lower energy bands.

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FIGURE CAPTION

Figures 1.1 — 1.15. The plot of $\log HR_{ij} - \log HR_{i'j'}$ for Sample 1.

Figures 2.1 — 2.15. The plot of $\log HR_{ij} - \log HR_{i'j'}$ for Samples 2 and 3, where an open circle represents a source of Sample 2 and a filled circle stands for a source of Sample 3.