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The Kolmogorov-Smirnov test for three redshift distributions of long gamma-ray bursts in the Swift Era *

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Abstract We investigate redshift distributions of three long burst samples, with the first sample containing 131 long bursts with observed redshifts, the second including 220 long bursts with pseudo-redshifts calculated by the variability–luminosity relation, and the third including 1194 long bursts with pseudo-redshifts calculated by the lag–luminosity relation, respectively. In the redshift range 0–1 the Kolmogorov-Smirnov probability of the observed redshift distribution and that of the variability-luminosity relation is large. In the redshift ranges 1–2, 2–3, 3–6.3 and 0–37, the Kolmogorov-Smirnov probabilities of the redshift distribution from lag–luminosity relation and the observed redshift distribution are also large. For the GRBs, which appear both in the two pseudo-redshift burst samples, the KS probability of the pseudo-redshift distribution from the lag–luminosity relation and the observed reshift distribution is 0.447, which is very large. Based on these results, some conclusions are drawn: i) the V-$L_{\rm iso}$ relation might be more believable than the τ-$L_{\rm iso}$ relation in low redshift ranges and the τ-$L_{\rm iso}$ relation might be more real than the V-$L_{\rm iso}$ relation in high redshift ranges; ii) if we do not consider the redshift ranges, the τ-$L_{\rm iso}$ relation might be more physical and intrinsical than the V-$L_{\rm iso}$ relation.

Key words: gamma rays: bursts — redshifts — distributions: statistical — KS test

1 INTRODUCTION

Gamma-ray bursts (GRBs) are powerful explosions in soft gamma-ray bands in the Universe, with some distinct characteristics: short duration times, high energies, and so on. Since the discovery of BATSE that the angular distribution of GRBs is isotropic in the sky, which suggested that GRBs are at cosmological distances (Meegan et al. 1992) and the afterglows were detected in 1997 (Costa et al. 1997; Frail et al. 1997; van Paradijs et al. 1997), it is generally accepted that GRBs lie at cosmological distances. Subsequently, GRBs are narrowly beamed (Sari et al. 1999) and the corresponding energies around 10^{51} erg are found (Frail et al. 2001; Piran et al. 2001). Because of their extreme energy release in gamma-ray bands and very wide redshift (z) range (by now the maximum of redshift detected is 6.29), GRBs are a promising new probe for the high-z Universe and become a new tool to investigate the related cosmology. GRBs are divided into two subclasses: short-hard and long soft bursts. This distinction is mainly based on the duration: long bursts with $T_{90} > 2$ s and short bursts with $T_{90} < 2$ s (Kouveliotou et al. 1993). Long bursts occur in the star-forming regions and their energy source is

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believed to be related to the collapse of the core of a massive star. Short bursts lie in early- and late-type galaxies, as well as field and cluster galaxies and their origin is thought to be the coalescence of compact binary systems (double neutron stars or a neutron star and a black hole) (Nakar 2007). In this work, we limit our analysis to the class of long bursts.

The redshift of GRBs can not only determine the luminosity, distance, as well as other physical parameters, but also combine some relations to constrain cosmology parameters (Dai et al. 2004; Ghirlanda et al. 2006). GRBs are highly transient events and fade rapidly. Their distances are very difficult to measure. Only spectroscopy can provide reliable redshifts. Therefore, to measure their redshift requires telescopes that make spectral observations within a short time after the burst. The Swift Mission (Gehrels et al. 2004) is designed mainly to rapidly detect, locate, and observe gamma-ray bursts. Thanks to the Swift, the number of the bursts with known redshifts increases rapidly.

Previous studies have discovered that long bursts have some relationships between GRB spectral characteristics and collimation corrected energetics, and between prompt observables and afterglow observables. These relations are usually applied to determine the GRB redshifts or as a tool to constrain the cosmology parameters (see the review paper by Ghirlanda et al. 2006). In these relations, the lag (τ)–luminosity ($L_{\rm iso}$) relation found by Norris et al. (2000), and variability (V)–luminosity relation found by Fenimore & Ramirez-Ruiz (2000) and Reichart et al. (2001), have been used as a pseudo-redshift indicator to estimate z for a large population of GRBs (Band et al. 2004; Fenimore & Ramirez-Ruiz 2000). The V-$L_{\rm iso}$ relation has also been further tested and confirmed (Guidorzi 2005; Li & Paczyński 2006; Rizzuto et al. 2007). The possible interpretations of the τ-$L_{\rm iso}$ relation (see the review paper by Ghirlanda et al. 2006) include the effect of spectral softening of GRB spectra (Schaefer 2004; Daigne & Mochkovitch 2003) during the prompt emission due to radiative cooling (Crider et al. 1999) or a kinematic origin due to the variation of the line-of-sight velocity in different GRBs (Salmonson 2000) or the viewing angle of the jet (Ioka & Nakamura 2001). But the V-$L_{\rm iso}$ relation interpretations mainly invoke the presence of a jet, whose angle θ, i.e. either the opening angle or the viewing angle (e.g., see Ioka & Nakamura 2001) for some jet patterns, is strongly connected with the observed peak luminosity L as well as with the Lorentz factor Γ of the expanding shell(s) (Rizzuto et al. 2007). Although physical explanations for the two relations have been proposed, validity of these relations are currently being debated and need further observations to test and theories to interpret. In this paper, we will introduce another method which compares the observed redshift distribution and the pseudo-redshift distributions estimated from the two relations, respectively. The advantage of this approach is to test the validity of the two relations, which is different from the direct testing of these relations.

This paper is organized as follows. In Section 2, we describe three samples of the redshift, and investigate the three redshift distributions. Then in Section 3, we select 193 GRBs which appear both in Sample 2 which comes from the V-$L_{\rm iso}$ relation and Sample 3 which comes from τ-$L_{\rm iso}$ relation, and investigate whether the redshifts calculated with the two different relations are correlated. Finally, brief discussion and conclusions are presented in Section 4.

2 THE REDSHIFT DISTRIBUTIONS OF THE THREE REDSHIFT SAMPLES

We obtained the observed GRB redshifts through the webpage (*http://www.mpe.mpg.de/∼jcg /grbgen.html*) and the swift webpage (*http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table.html/*). In these redshifts, we only chose the long bursts and used the low limit for those GRBs with no accurate redshift value. Up to February 11, 2008, we got 131 long bursts with known redshifts, and denoted them as Sample 1. Fenimore & Ramirez-Ruiz (2000) have found the V-$L_{\rm iso}$ relation and used it to calculate the redshifts for 220 long bursts; these GRB redshifts were denoted as Sample 2. In 2004, Band et al. (2004) used the τ-$L_{\rm iso}$ relation to calculate self-consistent redshifts for a large sample of long BATSE gamma-ray bursts, where we obtained 1194 GRBs with pseudo-redshifts, which was denoted as Sample 3.

If a relation is true and physical, then the redshift distribution obtained from it should reflect the true redshift distribution, i.e., the calculated redshift distribution should not have an obvious difference from the observed redshift distribution. Based on this idea, we first investigated the three redshift distributions.

They are presented in Figure 1. From Figure 1, we can find that the main peak of the three distributions all lie around 1, and two smaller peaks of the three distributions lie in the redshift ranges 2–3 and 3–4, respectively. This shows that the three distributions have a similar shape and trend, and share some important characteristics.

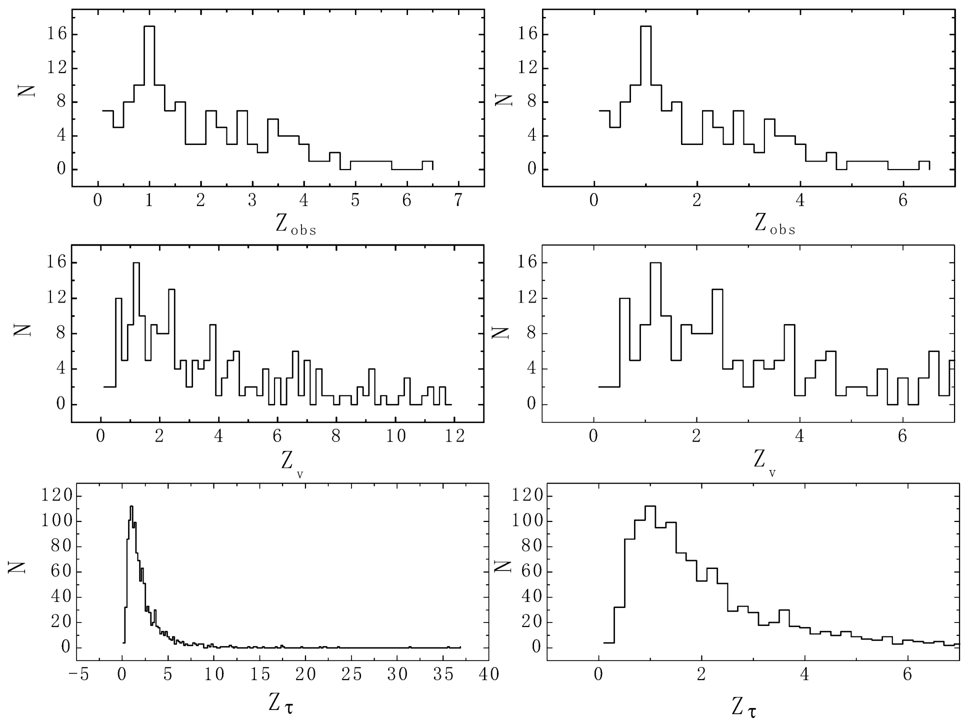

Fig. 1 The redshift distributions of the three redshift samples. The plots in the left column include all the GRBs, but the plots in the right column only include the GRBs whose redshift is less than 7.

Subsequently, we applied the Kolmogorov-Smirnov (KS) test to the three distributions. The redshift range of Sample 1 is only from 0 to 6.29. The observed redshift number is not big enough, and it is in a small redshift interval, so the observed redshift number is too small to make further statistical research. We divided the redshift range into five catagories to calculate their corresponding KS probabilities. The five redshift ranges were 0–1, 1–2, 2–3, 3–6.3, and all GRBs, respectively. The numbers of the three samples in the five redshift ranges are presented in Table 1, respectively. The corresponding KS test was

Table 1 The mean, median and the KS probability of the three distributions for the five redshift ranges.

Z range	n1	n2	n3	mean1	median1	mean2	median2	mean3	median3	p1	p2	p3
0–1	48	36	335	0.598	0.693	0.658	0.700	0.674	0.691	0.740	0.046	0.300
1–2	30	46	391	1.390	1.323	1.517	1.500	1.438	1.409	0.123	0.435	0.167
2–3	25	30	204	2.445	2.430	2.453	2.400	2.411	2.337	0.596	0.611	0.121
3–6.3	28	52	194	3.958	3.699	4.340	4.200	4.175	3.959	0.157	0.453	0.572
all	131	220	1194	1.850	1.477	4.233	2.950	2.416	1.584	0.478E-07	0.240	0.823E-13

NOTE: In this table, 1, 2 and 3 represent Samples 1, 2 and 3, respectively; n1, n2 and n3 represent the number of Samples 1, 2 and 3 in different redshift ranges, respectively; p1 represents the KS probability between Samples 1 and 2; p2 represents the KS probability between Samples 1 and 3; p3 represents the KS probability between Samples 2 and 3.

performed for each of the five ranges among the three distributions. The KS probabilities are presented in Table 1 and Figure 2.

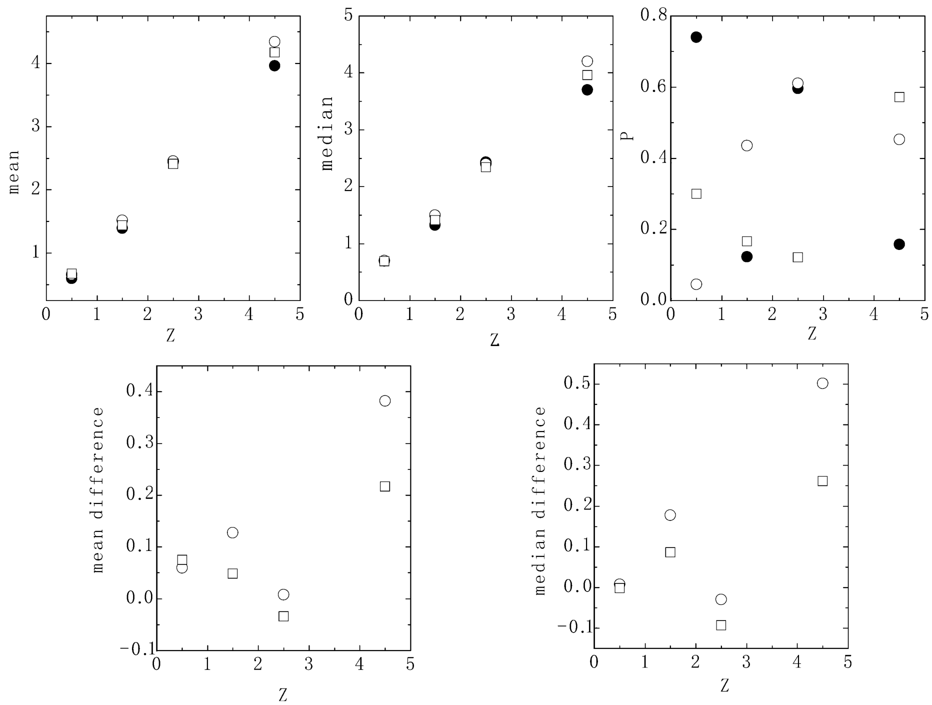

Fig. 2 The mean, mean differences, median, median differences and the KS probability of the three distributions for four cases. For the left two plots in upper row, the solid circles, opened circles and opened squares represent Samples 1, 2 and 3, respectively. For the right plots in upper rows, the solid circles, opened circles and opened squares present the KS probabilities between Samples 1 and 2, between Samples 1 and 3, and between Samples 2 and 3, respectively. For the two plots in the bottom row, the open circles and the open squares represent the difference between Samples 1 and 2, Samples 1 and 3, respectively.

In Figure 2, the mean and median of the three distributions in different redshift ranges are also plotted. At the same time, we also calculate the mean differences and median differences between Samples 1 and 2, between Samples 1 and 3, which are presented in Figure 2. From Figure 2, we can find that for the first three redshift ranges, the mean and median of the three samples do not obviously appear different. In fact, they are almost in superposition. But for the fourth redshift range, the means and medians of the three samples are obviously different, and they are smallest for the observed redshift and are biggest for Sample 2. From Figure 2, this can be further demonstrated that in the first three redshift ranges, the mean differences and the median differences are around 0 and they are around 0.4 in the fourth ranges. From Figure 2 and Table 1, we find that the KS probabilities of Samples 1 and 2 in the range 0–1 and 2–3 are very big, suggesting that they arise from the same distribution in these redshift ranges. For Samples 1 and 3, the KS probability in the range 0–1 is small but in the ranges 1–2, 2–3, and 3–6.29, it is large. This shows that the redshift distribution of Sample 3 is different from Sample 1 in the range 0–1 and does not appear obviously different from Sample 1 in the ranges 1–2, 2–3, and 3–6.29. For the three samples that include all the GRBs, the KS probabilities of Samples 1 and 2 is 0.478E-07 and it is 0.240 for Samples 1 and 3, which suggests that Samples 3 and 1 arise from the same distribution on the whole. Thus, the study above can lead to the following conclusions: Firstly, for the low redshift ranges, the

V-$L_{\rm iso}$ relation may be more physical and intrinsical, but for the high redshift ranges, it should not be correct. Secondly, the τ-$L_{\rm iso}$ relation is probably not be real and physical in the redshift range 0–1 and it should be physical and intrinsical in the high redshift ranges. Finally, if the two relations are all physical, but they are different for low and high redshift GRBs, then we can suppose that the low redshift GRBs are different from high redshift GRBs.

3 COMPARISONS OF 193 REDSHIFTS CALCULATED FROM THE TWO RELATIONS

A GRB redshift can be calculated with the τ-$L_{\rm iso}$ relation or the V-$L_{\rm iso}$ relation. In the previous paragraph, we found that the KS probability of Samples 2 and 3 is 0.824E-13, which is very small, suggesting that it is unlikely that the two distributions arise from the same distribution. As Sample 3 includes most of the long bursts detected by BATSE, most of the bursts in Sample 2 can be found in Sample 3. Thus, from the Samples 2 and 3, we selected the GRB which appears in both samples. The total number of these GRBs is 193. The 193 GRBs selected from Sample 2 are signed as Sample 4 and those selected from Sample 3 are signed as Sample 5. In Figure 3, the correlation between the redshift from the V-$L_{\rm iso}$ relation and the redshift from the τ-$L_{\rm iso}$ relation is plotted, and in this figure, the distribution of the ratio of the redshift of Sample 5 to the redshift of Sample 4 is also plotted.

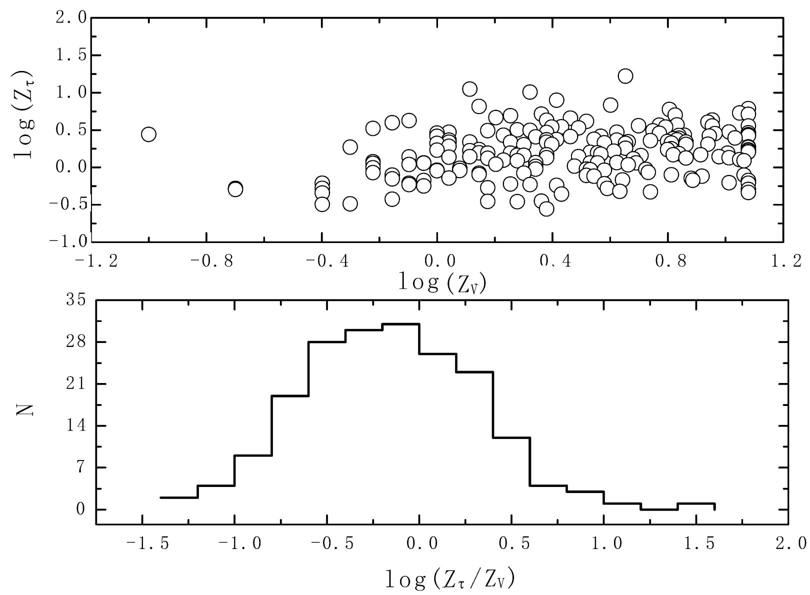

Fig. 3 Upper plot: the correlation between $\log(Z_\tau)$ and $\log(Z_V)$ for Samples 4 and 5. Lower plot: the distribution of the ratio of the redshift of Sample 5 to that of Sample 4.

The mean and median of Sample 4 are 4.315 and 3.1, and those of Sample 5 are 2.109 and 1.566. The KS probability of Samples 4 and 5 is 6.859E-10, which shows that the redshift distributions of Samples 4 and 5 are obviously different and unlikely to arise from the same distribution, indicating that the two relations are not equivalent for calculating the same GRB redshift. The KS probability is 0.447 for Samples 1 and 5 and it is 1.209E-08 for Samples 1 and 4, which suggest that the redshift distribution of Sample 1 is consistent with that of Sample 5 and they should arise from the same distribution. For the 193 GRBs, each GRB should have one and only one redshift. If the two relations can be used to estimate the correct redshift, they should lead to the same redshift, or the redshifts calculated from the two relations should be similar or correlated. However, from Figure 3, we can find that most of the ratios of the two redshifts are less than 1, i.e., most of the redshifts calculated from the τ-$L_{\rm iso}$ relation are less than that from the V-$L_{\rm iso}$ relation. In addition, from Figure 3, we can also not find any correlation between the two redshifts, and for a GRB, the redshifts from the different relations are obviously different, which further tells us that the two relations are not consistent when calculating the redshift. We can also conclude that the τ-$L_{\rm iso}$ relation might be more physical than the V-$L_{\rm iso}$ relation.

4 DISCUSSION AND CONCLUSIONS

In this paper, we investigate the redshift distributions of the observed long bursts with known redshifts (Sample 1), 220 long bursts with the pseudo–redshifts calculated from the V-$L_{\rm iso}$ relation (Sample 2) and 1194 long bursts with the pseudo–redshifts calculated from the τ-$L_{\rm iso}$ relation (Sample 3). The KS tests of the three distributions in the five cases are performed. We find that in different redshift ranges, the KS probabilities among the three distributions appear different. In the redshift range 0–1, the KS probability of Samples 1 and 2 is 0.74, which is so large that one can only consider that the two distributions should arise from the same distribution. For Samples 1 and 3, it is only 0.045 and it is much smaller than that of Samples 1 and 2, which shows that in the redshift range 0–1, Sample 3 might not be a better representation for real GRB redshift distribution than Sample 2. However, in high redshift ranges, from Figure 2, one can find that the KS probabilities of Samples 1 and 3 are large, suggesting that the two distributions are consistent and that they might arise from the same distribution in these redshift ranges. If for all the GRBs, the KS probability of Samples 1 and 3 is bigger than that of Samples 1 and 2, this suggests that the τ-$L_{\rm iso}$ relation is more physical and intrinsical than the V-$L_{\rm iso}$ relation. Based on these facts, we think that the V-$L_{\rm iso}$ relation should be a better pseudo–redshift indicator for low redshift GRBs and that the τ-$L_{\rm iso}$ relation should be a better pseudo–redshift indicator for high redshift GRBs. What reasons lead to this conclusion? We think that maybe there are two reasons : one is that the low redshift GRBs might be physically different from the high redshift GRBs, and the other is that the two relations might not be physical, but rather are only exterior relations. Now, we cannot know which is true, and it is an open question.

We have also studied GRB which appears in both Samples 2 and 3. The total number of these GRBs is 193. For all of these 193 GRBs, there are two pseudo–redshifts calculated from the two relations. If the two relations have the same effect on estimating the redshift and give the correct redshifts, the redshifts for a GRB with different relations should be similar or correlated and should not have an obvious discrepancy. But in fact, the two pseudo–redshift distributions are different and the pseudo–redshift of most of the 193 GRBs from the τ-$L_{\rm iso}$ relation is less than that from the V-$L_{\rm iso}$ relation and they are also not correlated. The probability of the KS test from Samples 1 and 4 is very small, suggesting that they are unlikely to arise from the same distribution, but the probability of the KS test from Samples 1 and 5 is very large, suggesting that the two samples should arise from the same distribution.

Based on our results and the above discussion, we can draw some conclusions: Firstly, the V-$L_{\rm iso}$ relation might be more believable in low redshift ranges and the τ-$L_{\rm iso}$ relation might be more real in high redshift ranges. This tells us that we could use the V-$L_{\rm iso}$ relation to calculate the GRB low redshift distribution and use the τ-$L_{\rm iso}$ relation to obtain the high redshift distribution for further GRB studies. Secondly, if we do not consider the redshift ranges, the τ-$L_{\rm iso}$ relation might be more physical and intrinsical than the V-$L_{\rm iso}$ relation. Finally, we suggest that there are some important differences between low redshift GRBs and the high redshift GRBs. This is only a hypothesis which should be tested in a future study.

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