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A possible use of Fourier Transform analysis method as a distance estimator

H.-Y. Chang[1], S.-J. Yoon[2], and C.-S. Choi[3]

[1] Korea Institute for Advanced Study 207-43 Cheongryangri-dong, Dongdaemun-gu, Seoul 130-012, Korea
e-mail: hyc@ns.kias.re.kr

[2] Center for Space Astrophysics and Department of Astronomy Yonsei University, 134 Shinchon-dong Seodaemun-gu, Seoul 120-749, Korea
e-mail: sjyoon@csa.yonsei.ac.kr

[3] Korea Astronomy Observatory 36-1 Hwaam-dong, Yusong-gu, Taejon 305-348, Korea
e-mail: cschoi@kao.re.kr

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Abstract. We speculate on the possibility of using the Fourier transform analysis method as a distance estimator of the observed gamma-ray bursts (GRBs). It is based on a hypothetical empirical relation between the redshift and the power-law index of power density spectra (PDSs) of the observed GRBs. This relation is constructed by using the fact that the observed power-law index is dependent upon a characteristic timescale of GRB light curves. The rms error of redshift estimates is 0.42 for an empirical relation obtained with the 7 long ($T_{90} > 15$) GRBs observed by the BATSE whose redshift information is available. We attempt to determine the spatial distribution of the GRBs observed by the BATSE as a function of redshifts on the basis of the resulting redshift estimator. We discuss possible uncertainties of the suggested method.

Key words. cosmology: theory – gamma rays: bursts – methods: data analysis

1. Introduction

Since gamma-ray bursts (GRBs) were first discovered in late 60's (Klebesadel et al. 1973), thousands of GRBs have been detected up to date. The discovery of afterglows in other spectral bands and host galaxies enabled us to measure redshifts of about twenty GRBs (see, e.g., http://www.aip.de/∼jcg/grbgen.html), establishing the fact that GRBs are indeed cosmological (Mao & Paczyński 1992; Meegan et al. 1992; Piran 1992; Metzger et al. 1997). Nonetheless, the redshifts are still unknown for most of the detected GRBs. Unless we locate a burst on the sky by immediate follow-up observations, the distance of the burst is apt to remain unrevealed.

Concerning physical models of GRBs, their distance scales are related to key issues, such as, energetics, burst rates as a function of redshifts. That is, estimating the distance puts direct constraints on the theories of the observed GRBs. Besides this the redshift distribution of GRBs should track the cosmic star formation rate of massive stars, if GRBs are indeed related to the collapse of massive stars (Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999). Therefore, once its association has been proven, one expects the observed GRBs are the most powerful probe of the high redshift universe (Wijers et al. 1998; Blain & Natarajan 2000; Lamb & Reichart 2000). In fact, the GRB formation rate and the star formation rate (SFR) have similar slopes at low redshift, implying that GRBs can be used indeed as a probe of the cosmic star formation rate at high redshift.

At present, there are too few redshift measurements with which to produce the global GRB formation rate. This fact is indeed hard to avoid unless observers set up networks of efficient telescopes in order for an immediate follow-up observations. Recently, however, there are pilot studies to overcome the technical ability mentioned above (e.g., Reichart et al. 2001), though there have been several attempts to quantify pulse shapes of GRBs and interpret results in terms of GRB physics (Fenimore et al. 1996; Norris et al. 1996; In'T Zand & Fenimore 1996; Kobayashi et al. 1997; Daigne & Mochkovitch 1998; Fenimore 1999; Panaitescu et al. 1999). Several authors (Stern et al. 1999; Fenimore & Ramires-Ruiz 2000; Reichart et al. 2001) began to observe strong correlations between temporal properties of the observed GRBs and their brightness, which may have some implications that the measured spikiness can be used to obtain distances much like a Cepheid-like distance estimator. Norris et al. (2000) also showed the

Send offprint requests to: H.-Y. Chang,
e-mail: hyc@kias.re.kr

spectral lag/luminosity relationship for six bursts with known redshifts can be appreciated. Currently, the luminosity estimator yields best-estimate luminosity distances that are accurate to a factor of ≈2 (see Reichart et al. 2001).

Along the line of efforts of such kinds we propose a new method based on an empirical relation motivated by the work of Chang (2001). It is well known that power density spectra (PDSs) of long GRBs show a power-law behavior (Beloborodov et al. 1998, 2000). Though its underlying physical mechanism is not obvious (Panaitescu et al. 1999; Chang & Yi 2000), the PDS analysis may provide useful information of physics of GRBs (Panaitescu et al. 1999) and the distance information (Chang 2001). Particularly, Chang (2001) has demonstrated that the power-law index of PDSs of the observed GRBs shows a redshift dependence, implying a possible relationship between the power-law index and the redshift of GRBs. It can be possibly worked out because of the fact that burst profiles should be stretched in time due to cosmological time dilation by an amount proportional to the redshift, $1 + z$.

In Sect. 2 we begin with a brief summary of the PDS analysis in GRB studies, and describe the empirical relation involved in our procedure. In Sect. 3 we present results obtained by applying our method to the GRBs observed by the BATSE instrument aboard the *Compton Gamma Ray Observatory* (Paciesas et al. 1999), and discuss what they suggest. Finally, we conclude by pointing out that the accuracy of our redshift estimates is limited by unknown underlying properties of GRBs and what should be further developed in Sect. 4.

2. Empirical relation of power-law index and redshift

Contrary to the diverse and stochastic behavior in the time domain, long GRBs show a simple behavior in the frequency domain (e.g., Beloborodov et al. 1998). The power-law behavior is seen even in a single burst when it is bright and long. The power-law PDS provides a new tool for studies of GRBs themselves. Using the PDS analysis, Panaitescu et al. (1999) analyzed the temporal behavior of GRBs in the framework of a relativistic internal shock model. They set up their internal shock model and attempted to identify the most sensitive model parameters to the observed PDS, which is defined by the square of the Fourier transform of the observed light curve. They concluded that the wind must be modulated such that collisions at large radii release more energy than those at small radii in order to reproduce consistent PDSs with the observation.

Another valuable use of the PDS analysis can be realized bearing in mind that for a given sampling interval the resulting power-law index is dependent upon the characteristic timescale of the observed light curve. This should be true because cosmological objects like GRBs should not only be redshifted in energy but also extended in time because of the expansion of the universe.

Table 1. A list of the GRBs used in the analysis with the redshifts and T_{90}. The redshifts are quoted from a complied table at `http://www.aip.de/~jcg/grbgen.html`

GRB name	trigger number	redshift	T_{90} (s)
GRB 991216	7906	1.02	15
GRB 990510	7560	1.619	68
GRB 990506	7549	1.3	130
GRB 990123	7343	1.60	63
GRB 980703	6891	0.966	411
GRB 980425	6707	0.0085	34
GRB 970508	6225	0.835	23

Chang (2001) demonstrated that a cosmological time dilation effect is indeed imprinted in the light curves of the observed GRBs whose redshifts are known by dividing the GRBs into near and far groups. The author has showed that the near GRB group ends up with the smaller power-law index than the far one and that the correction with the $1 + z$ factor removes the differences, and that the power-law index difference in two separate groups is larger than that among different energy bands.

In order to construct the empirical relation between the power-law index and the redshift of GRBs we have calculated the power-law index of the PDSs of 7 GRBs detected by the BATSE with known redshifts. We have used light curves of the GRBs from the updated BATSE 64 ms ASCII database[1]. From this archive we select the light curves of the GRBs in channel 2 whose redshifts are available. We list up the GRBs used in our analysis with their reported redshifts in Table 1. We calculate the Fourier transform of each light curve of the GRBs and the corresponding PDS. Before taking the Fourier transform of light curves we scale them such that the height of their highest peak has unity in the GRB light curves. Since the individual PDS of GRBs are stochastic, different parts of the PDS appear to follow a slightly different power-law index. Having calculated the PDS of an individual GRB we obtain the power-law index of the PDS using the limited part of the PDS, i.e., $-1.6 < \log \nu < 0$. The lower bound is roughly determined in that the deviation from the power law begins due to the finite length of bursts. The upper bound is where the Poisson noise becomes dominant. Poisson noise in the measured count rate affects the PDS at high frequencies and has a flat spectrum. The Poisson noise level equals the burst total fluence including the background in the considered time window. We calculate the individual Poisson level for each burst and subtract it from the burst PDS.

The PDSs can be described as a single power law with superimposed fluctuations which follow the exponential distribution, which may require the maximum likelihood method. However, by considering that we smooth the PDSs on the scale $\Delta \log \nu = 0.5$ before fitting, the least squares fit can be preferred since the error

[1] `ftp://cossc.gsfc.nasa.gov/pub/data/batse/`

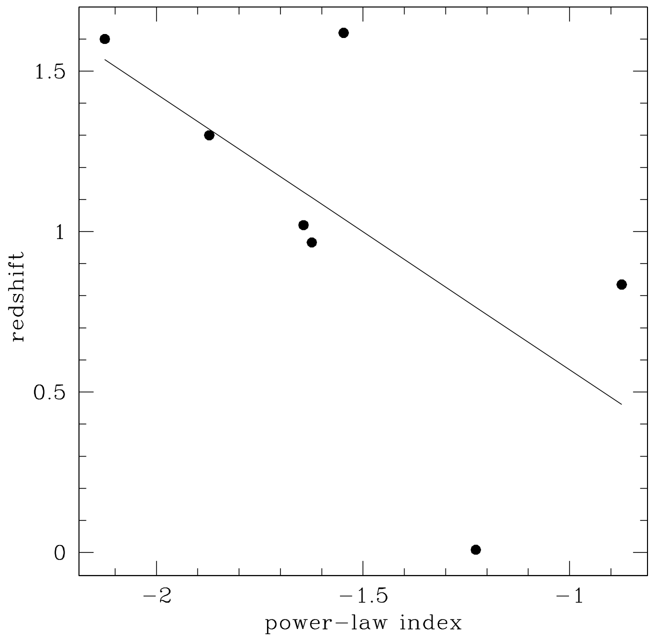

Fig. 1. Relation of power-law index and redshift. The dots are obtained data and the line results from fitting of individual PDSs by the least squares fit.

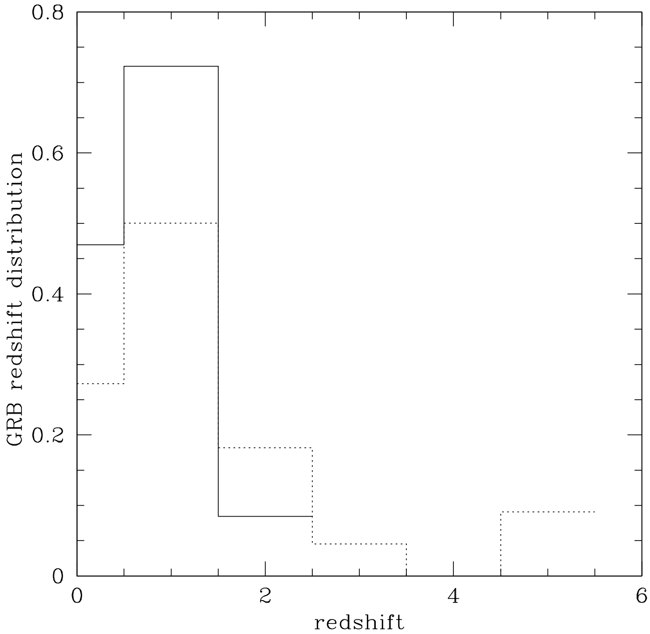

Fig. 2. Normalized spatial distributions of 388 long GRBs observed by the BATSE are compared with that of the redshift-known GRBs, indicated by the solid line and the thin dotted line, respectively.

distribution may be modified to the normal distribution according to the *central limit theorem*. We have used two different fitting routines corresponding to the normal error distribution and the exponential error distribution. We compared both fitting algorithms and concluded they led little difference. What is shown in Fig. 1 are an empirical relation between the redshift and the power-law index, and the best linear-fit obtained by the least squares fit. The linear empirical relation we use here is obviously not unique. It is only a trial relation to demonstrate a possible usefulness of Fourier Transform analysis method as a distance estimator. We also have attempted higher order polynomial fits but it did not end up with a monotonic relation as one should expect.

The error estimate of z, which are defined by a square root of the average of squared difference between the measured redshifts summarized in Table 1 and the expected redshifts by the fitting, is 0.42. Initially we had 9 GRBs available in our analysis, but we have decided to remove GRB 971214 from our data, because it is such a dim burst that a signal-to-noise ratio is not good enough. We also included GRB 980329 as an upper limit, and later excluded this data point since we have confined our data set to the GRBs whose redshifts are measured spectroscopically. Adding this point makes a slope a bit steeper in Fig. 1, but little difference in Fig. 2, even though it is true that a fit becomes degraded in the sense that the rms error becomes larger.

3. Spatial distribution of GRBs

We adopt light curves of the long GRBs from the updated BATSE 64 ms ASCII database as in processes above. We choose bursts with durations $T_{90} > 20$ s, where T_{90} is the time it takes to accumulate from 5% to 90% of the total fluence of a burst summed over all the four channels. Of those bursts, we further select bursts with the peak count rates satisfying $C_{\rm max}/C_{\rm min}$ for the 64 ms trigger timescale is greater than 1. Applying these criteria, we end up with 388 bursts.

In a similar way, we obtain power-law indices of PDSs of the selected GRBs and subsequently estimates of their redshifts. In Fig. 2, the redshift distributions of the GRBs obtained by the relation we have in the previous section are shown. Note that the dotted histogram represents the spatial distributions of the 20 GRBs whose redshifts are available at the web site, from where the quoted redshifts in Table 1 are taken. Among the available redshift information we have adopted the spectroscopic redshifts. It is interesting to note that the predicted redshift distribution of GRBs appear marginally consistent with that of the GRBs with redshift-known.

4. Discussions and conclusion

There are problems and limits to determine redshifts accurately in both obtaining the relation and applying this relation to data. First of all, even though this method is in principle to work, we need to understand clearly what and how forms the flat part of PDS, in other words, the dependence of the observed slope on the redshift. We have implicitly assumed that all the long GRBs have a more or less same characteristic timescale and cosmological time dilation alone affects varying the characteristic timescale. With all the efforts in implementing a sophisticated algorithm to accommodate the diversity of the light curves, it is essential to understand a fundamental mechanism of GRBs to derive the intrinsic relation of the power-law index and the redshift. Secondly, the effect of redshift tends to flatten PDSs of GRBs on the contrary to the time dilation effect. It reflects a well-known fact that pulses in a single GRB are more narrow in a higher energy band (e.g., Norris et al. 1996). These effects combine and produce undesirable results in obtained power-law index. We have presumed in this study that the time dilation effect on the power-law index is larger than that of the redshift as observed in Chang (2001) and ignored the effect of the redshift. However, it should be understood how the power-law index relates with the energy channels to improve the proposed method accommodating the redshift effect. Thirdly, the source-frame power-law index might be a function of the peak luminosity of the burst. Since only high luminosity bursts are bright enough to be observed at high redshifts, one would artificially get a trend with redshift. This trend would in reality depend on the sensitivity of BATSE, and would be proved or disproved in the Swift era.

We speculate on the possibility of use of the Fourier transform analysis method as a distance estimator of the observed GRBs. Even though the estimator we present in this paper is not yet robust, we doubt that it is impossible to determine distances of individual GRBs with this approach. Nonetheless, redshift estimates are subject to the stochastic nature of the observed PDSs and accuracy of estimates are limited by unknown properties of the GRBs. One of the encouraging conclusions of this study is, however, that redshifts of the GRBs can be obtained with the GRB light curves whose redshifts otherwise remain unknown forever. Robustness of this method we suggest can be proved or disproved as data accumulate. Availability of more redshifts of GRBs may help to reproduce a better empirical relation and consequently a more accurate distance estimator.

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